# Enhancement/Upgrade of Engine Structures Technology Best Estimator (EST/BEST) Software System

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# Foreword

This report represents a summary of the technical work performed during the entire contract period for the Order No. C-76751-J entitled "Enhancement/upgrade of the EST/BEST (Engine Structures Technology Benefits Estimator) Software System." ALCCA module has been integrated with the EST/BEST software system and the documentation for the work performed has been completed. Also, the EST/BEST software system package has been prepared and delivered along with.

## SUMMARY OF ACTIVITIES:

The following sections of the report describes the work performed during the contract period and the capabilities included in the EST/BEST software system. The developed EST/BEST software system includes the integrated NESSUS, IPACS, COBSTRAN and ALCCA computer codes required to perform the engine cycle mission and component structural analysis. Also, the interactive input generator for NESSUS, IPACS and COBSTRAN computer codes have been developed and integrated with the EST/BEST software system. The input generator allows the user to create input from scratch as well as edit existing input file interactively. Since, it has been integrated with the EST/BEST software system, it enables the user to modify EST/BEST generated files and perform the analysis to evaluate the benefits. Appendix A gives details of how to use the newly added features in the EST/BEST software system.

Highlights of the added capabilities and further testing of the EST/BEST software system are as follows:

(I)     INTEGRATION OF THE NESSUS COMPUTER CODE WITH EST/BEST SOFTWARE SYSTEM:

The NESSUS computer code and the developed interactive input generator modules have been integrated with the EST/BEST software system. The existing capabilities in the in the integrated EST/BEST software system have been enhanced as well as improvements on the results have been made. The highlights of the capabilities are summarized below:

- User can generate the following input required to perform the probabilistic structural analysis using NESSUS:

    - Nodal Coordinates
    - Element connectivity
    - Boundary conditions
    - Mechanical loads such as point loads, nodal pressures, distributed pressure load, centrifugal forces
    - Thermal loads. Each layer temperature can be interpolated by providing top and bottom surface temperatures and specifying the interpolation method.
    - Analysis options: static, frequency with and without stress stiffening and buckling

- ♦ Primitive random variables related geometry, boundary conditions, mechanical and thermal loads, etc., their probability distributions and perturbations.
- ♦ Probabilistic analysis methods: mean value first order analysis (MVFO) and advanced mean value first order analysis (AMVFO). The user can perform both non-iterative as well as iterative probabilistic methods. MVFO provides faster solution whereas the AMVFO can be used for structures with non-linear responses where convergence of probability needs iterations.
- ♦ Output request definitions.
- The entire input can be prepared using default options and/or non-default options.
- The geometry can be generated using the integrated COBSTRAN computer code. User can generate the coordinates and connectivity for complicated structures like blades with a minimal input.
- User can edit the COSMO generated NESSUS file and enhance the input data for other NESSUS features.
- Input can be prepared in one or more sitting sessions (for larger problems).
- Each individual input set can be created through direct keyboard entry or by importing files containing the respective input set e.g. thermal loads can be read from the file also.
- Program checks for consistency of the input and eliminates possible general errors made by the user.
- Previously available options related to NESSUS have been kept intact.

Additional capabilities were demonstrated by performing the probabilistic analysis of the high-pressure compressor blade. Static, frequency (with and without stress stiffening) and buckling analyses were performed for the High Speed Civil Transport engine blade. The problem details of the results were submitted in the monthly progress reports and are attached in Appendix B.

Graphical User Interface (GUI) in the EST/BEST system was modified/updated to enable the use of additional NESSUS features. The typical updated GUI screens are given in the Appendix C.

(II)    INTEGRATION OF THE IPACS COMPUTER CODE WITH EST/BEST SOFTWARE SYSTEM:

The IPCAS computer code (with FORTRAN 77 features) received from Mr. Chuck Putt was debugged and tested for static, frequency with and without stress stiffening, and buckling analysis capabilities. Several problems related to these analyses options were fixed and verified. The IPACS code is made available as stand alone as integrated computer code with EST/BEST.

The IPACS computer code and the developed interactive input generator modules have been integrated with the EST/BEST software system. The existing capabilities in the in the integrated EST/BEST software system have been enhanced as well as improvements on the results have been made. The highlights of the capabilities are summarized below:

- User can generate the following input required to perform the probabilistic structural analysis using IPACS:

  - Nodal Coordinates
  - Element connectivity
  - Boundary conditions
  - Mechanical loads such as point loads, nodal pressures, distributed pressure load, centrifugal forces
  - Thermal loads. Each ply temperature can be interpolated by providing top and bottom surface temperatures and specifying the interpolation method.
  - Analysis options: static, frequency with and without stress stiffening and buckling
  - Composite properties uncertainty definitions of the constituents, fabrication and geometry variables. The mean values of the constituents are retrieved directly from the material property database based on the constituent keyword name. Thus, the user input is minimized.
  - Ply group and arrangement definitions on the structure.
  - Primitive random variables related geometry, boundary conditions, mechanical and thermal loads, etc., their probability distributions and perturbations. Thermal loads can be fully or partially correlated random variables.
  - Perturbation magnitude definitions.
  - Ply response table and structural response definitions for the desired output.
  - Output request definitions.
- The entire input can be prepared using default options and/or non-default options.
- The geometry can be generated using the integrated COBSTRAN computer code. User can generate the coordinates and connectivity for complicated structures like blades with a minimal input.
- User can edit the COSMO generated IPACS file and enhance the input data for other IPACS features.
- Input can be prepared in one or more sitting sessions (for larger problems).
- Each individual input set can be created through direct keyboard entry or by importing files containing the respective input set e.g. thermal loads can be read from the file also.
- Program checks for consistency of the input, and eliminates possible general errors including those related to inter dependence of different input cards.
- Previously available options related to IPACS have been kept intact.

Additional capabilities were demonstrated by performing the probabilistic analysis of the COBSTRAN generated hollow blade. Static, frequency (with and without stress stiffening) and buckling analyses were performed for the hollow engine blade. The problem details of the results were submitted in the monthly progress reports and are attached in Appendix D.

Graphical User Interface (GUI) in the EST/BEST system was modified/updated to enable the use of additional IPACS features. The typical updated GUI screens are given in the Appendix C.

(III)    INTEGRATION OF THE COBSTRAN COMPUTER CODE WITH EST/BEST

Additional capability of generating mesh for complicated structures like hollow engine blade with and without spars was added and made operation in the COBSTRAN computer code. The input can be created or modify the existing input interactively. Also the mesh can be generated interactively and corresponding output files can be imported by NESSUS as IPACS computer codes. Such a capability minimizes the mesh data input in NESSUS and IPACS.

Inputs for the hollow blade with and without spars were generated using the integrated COBSTRAN computer code in the EST/BEST software system. Graphical User Interface was developed to integrate the COBSTRAN computer code and its interactive input generator module. The typical updated GUI screens are given in the Appendix C.

Added capabilities have been demonstrated by generating the input for a typical composite hollow blade with and without spars for an engine structure using the integrated COBSTRAN and the interactive input generator in the EST/BEST software system. The details of these capabilities were reported in the previous monthly reports.

Also, GUI programming to integrate ALCCA computer code in a modular fashion with the EST/BEST software system has been completed and analysis for a test problem has been done. The ALCCA module augments the existing FLOPS cost-analysis computation for the engine cycle missions and component/structures using new cost models. Further testing is in progress and is expected to be complete during the next reporting period.

(IV)    INTEGRATION OF THE ALCCA COMPUTER CODE WITH EST/BEST

The ALCCA (Aircraft Life Cycle Cost Analysis) computer code to perform the cost analysis of composite structure was integrated with the EST/BEST software system. Graphical User Interface required to integrate the code was developed. A sample problem to perform the cost analysis was run and the typical cost analysis results are listed in Appendix E. The ALCCA computer code can be used as a substitute to the FLOPS (Flight Optimization Code) for the engine cycle analysis. However, the current effort of integration is limited to the standalone version of ALCCA analysis. ALCCA computer code has cost analysis based on newer and advanced models.

(V)    PROBABILISTIC FATIGUE LIFE ANALYSIS OF COMBUSTOR LINER:

Probabilistic fatigue life cycle analysis of the combustor liner was performed as required by the NASA project manager. The NESSUS capability for the harmonic loads was used to compute the probabilistic responses of a combustor liner subject to high temperatures. Material properties were input using the elasticity matrix coefficients. The probabilistic analysis input file was received from Dr. S. Pai of the NASA Glenn Research Center. Several NESSUS analyses runs were made for different degraded D-matrix coefficients due to the cyclic loads. Material degradation of these coefficients was performed using the multi-factor-interaction-model

(MFIM). Probabilistic cyclic stresses and respective sensitivity factors were computed using NESSUS computer code.

Also, the material strength cumulative distribution function using the Weibull distribution was computed for different cyclic load cycles. The strength degradation was achieved using MFIM. Degradation due to both the temperature as well as cyclic load effects was accounted in the computation process. CDF of strength under different load cycles was computed. The life cycle curves at different probability levels generated using the results of probabilistic strength and stress. Also, the probability of failure as well as survival probability curves for different load cycles were developed. The details of the analysis were reported in the March 1997 monthly progress report and are attached in the Appendix F.

APPENDIX A:  USER'S GUIDE TO THE UPDATED EST/BEST SOFTWARE SYSTEM

## A.1 Interactive Input General Information

The structure of the IPACS input file reflects the modularity of each module.  The structured format helps the user locate specific input data and manually enter or edit it.  The IPACS input file can have any user-specified filename, but must have a .DAT extension.  The input file may consist of up to six input data blocks; the data blocks must be separated by delimiters beginning with the $ character.  If multiple sections are desired, they must be arranged in the following order:

$COB
- Automatic Mesh Generation Input -
- •
- •
- •

$PIC
- Material Property Uncertainty Input -
- •
- •
- •

$NES
- Finite Element Input -
- •
- •
- •

$RAN
- Structure Level Random Variable Input -
- •
- •
- •

$FPI
- Probabilistic Output Request Input -
- •
- •
- •

$EXE2
-Execution Control Input
- •
- •
- •

The delimiters may be abbreviated to the first four characters (i.e.  $COB, $PIC, $NES, $FPI).

The structure of the NESSUS input file is same as that is described in the NESSUS manual.

During interactive processing of NESSUS input blocks, scratch files may also be created with the following extensions and formatting:

IPACS/NESSUS <u>Body</u> <u>Force</u> <u>Block</u>  Card 1:  \*BODY, IBODY(I)
*input filename*.BODY  Card 2 (IBODY=1):  X-COMP(F), Y-COMP(F), Z-COMP(F)
  Card 2 (IBODY=2):  X1(F), Y1(F), Z1(F)
  Card 3 (IBODY=2):  X2(F), Y2(F), Z2(F)


IPACS/NESSUS <u>Boundary</u> <u>Conditions</u> <u>Block</u>
*input filename*.BOUND  Cards 1 thru N:  NODE #(I), DOF #(I), DISP(F)


NESSUS <u>Material</u> <u>Properties</u> <u>Block</u>
*input filename*.prop  Cards 1 thru N:  NODE #(I), NODE(J) ,(PROP(I),I=1,5)


NESSUS <u>Layer</u> <u>Temperature</u> <u>Block</u>
*input filename*.temp  Cards 1 thru N:  NODE #(I), NODE(J) ,(TEMP(I),I=1,5)


IPACS/NESSUS <u>Element</u> <u>Connectivity</u> <u>Block</u>
*input filename*.CONN  Cards 1 thru N:  ELEM #(I), INODE(I), JNODE(I), KNODE(I),
    NODE(I)


IPACS/NESSUS <u>Nodal</u> <u>Coordinates</u> <u>Block</u>
*input filename*.COORD  Cards 1 thru N:  NODE #(I), X(F), Y(F), Z(F), TH(F)


IPACS/NESSUS <u>Random</u> <u>Variable</u> <u>Coordinates</u> <u>Block</u>
*input filename*.CRDxxx  Card 1:  MEAN(F), STD DEV(F), DIST TYPE(I)
  Cards 2 thru N:  NODE #(I), X-SDF(F), Y-SDF(F), Z-SDF(F),
    TH-SDF(F)


IPACS/NESSUS <u>Distributed</u> <u>Loads</u> <u>Block</u>
*input filename*.DIST  Cards 1 thru N:  BEG ELEM(I), END ELEM(I), ICODE(I),
    TRAC(F), PRESS(F), BODY FORCE(F)


IPACS/NESSUS <u>Random</u> <u>Variable</u> <u>Distributed</u> <u>Loads</u> <u>Block</u>
*input filename*.DSTxxx  Card 1:  MEAN(F), STD DEV(F), DIST TYPE(I)
  Cards 2 thru N:  BEG ELEM(I), END ELEM(I), ICODE(I),
    TRAC SDF(F), PRESS SDF(F), BODY
    FORCE SDF(F)


IPACS/NESSUS <u>Duplicate</u> <u>Nodes</u> <u>Block</u>
*input filename*.DUPL  Cards 1 thru N:  MASTER NODE(I), SLAVE NODE(I)

IPACS/NESSUS Nodal Forces Block
*input filename*.FORCE          Cards 1 thru N:    NODE #(I), DOF #(I), FORCE(F)


IPACS/NESSUS Random Variable Forces Block
*input filename*.FRCxxx              Card 1:    MEAN(F), STD DEV(F), DIST TYPE(I)
                                Cards 2 thru N:    NODE #(I), DOF #(I), FORCE SDF(F)


IPACS Material Orientation Block
*input filename*.orie          Cards 1 thru N:    BEG NODE(I), END NODE(I), X-COMP(F),
                                                  Y-COMP(F), Z-COMP(F)


where xxx is a three-digit number identifying the random variable and where (I) indicates integer and (F) indicates floating point numbers.

The IPACS/NESSUS scratch files are useful in recovering data following a program abort or a system failure. To recover data, use the "Input Existing File" options found on many of the menus, after reentering the input module using a filename different than the one used in the previous run. The quantities found in each of these files are written in free format consistent with the IPACS/NESSUS convention. This feature also allows users to import their own mesh, boundary conditions, and loads from outside the input module. To import this data, use the scratch file naming convention described above and simply have the data read into the program.

**A.2 Detailed Description of the Interactive Input Module**

As described in section 3.1, the IPACS/NESSUS input file consists of five separate sections including automatic mesh generation module, a module to compute probabilistic composite material properties, probabilistic finite element analysis module, and probability algorithm module.

The IPACS code contains an interactive input module that allows the user to interactively create or edit an IPACS input file and submit it for processing. Interactive module enables an inexperienced user to prepare the input in a user-friendly manner in a short time without making common mistakes. This module allows creating or editing the input file with little or no knowledge of the file's structure and format, and thus allows an inexperienced user to run the code and come up to speed more quickly.

The interactive input module is designed for ease of use. An input session need not be completed in one sitting: once an IPACS input file has been created it can be saved and returned to later for further editing, or in order to enter the execution mode and run the code. (For example, the user can enter or change the finite element mesh inputs, save the entries or edits, exit the IPACS program, and return later to add or edit the material specifications.)

An input session is begun at the main menu, which offers six options that allow the user quick access to input functions (refer to Figure 3.2.1 of the IPACS manual). The six input options may be selected and run in any order. The options access a series of menus in which the user is prompted for information to enter or change.

**A.3 Batch Input**

IPACS input can be prepared manually or by using any other preprocessor and processing it in a batch mode. The procedure to prepare the input is described in the following section.

As described in section A.1, the input file is divided into several different blocks. The block pertaining to the automatic mesh generation data should not be used in the batch mode. Each of the material property uncertainty input and finite element input data blocks are divided into parameter and model data groups. The parameter group of a data block defines the size of the problem, whereas the model group of the data block contains the actual model data. In both the data blocks, the model group always follows the parameter group. Also, a 'END' card marks end of the parameter group in a data block. The $PIC input data block contains the data related to the material properties and the lay-up configuration of composites in the structure. The $NES input data block contains the actual finite element data. Detailed input information on each block is discussed below:

**A.3.1 Material Property Uncertainty Input Data Block:**

The material property uncertainty input data block begins with a '$PIC' card. The composite lay-up configuration and material property uncertainties are defined in this block.

Normally, the $PIC data block ends with the beginning of the $NES data block (i.e., with a '$NESSUS' card). Different key words (a key word always begins with an '*'; asterisk) used in the material property uncertainty data block are discussed below:

## A.3.1.1 Material Property Uncertainty Parameter Input Data Group:

CFEM
       The above card is used to flag ifemx (MV) analysis
$PICn
       where n = 0 is used if material properties PDF computation is desired
            = 1 is used material properties PDF computation is to be bypassed

*PROSOL
       The keyword PROSOL is used to define the probabilistic structural analysis solution method. The general format is
       *PROSOL
          NSOL
          NMCS
       where NSOL is the probabilistic solution method. Different available probabilistic solution methods and their NSOL values are given below:

NSOL =     21     PV Based method using fast probability integrator
      =     22     Monte Carlo simulation technique for material property related uncertainties
NMCS   =     No. of samples for Monte-Carlo simulation (required for NSOL = 22)

*INDZON
       The keyword INDZON is used to define the total number of statistically independent zones in the structure. The general input format is
       *INDZON
          NDZON
       where NDZON is the total number of independent zones in a composite structure.

*PLYGRP
       The keyword PLYGRP is used to specify the total number of ply groups in each independent zone. The general input format is

       *PLYGRP
       INDI(1)            NLGRP(1)
       INDI(2)             NLGRP(2)
       INDI(3)             NLGRP(3)
       .                          .
       .                          .
       .                          .
       INDI(n)             NLGRP(n)

Where INDI is the independent zone no. NLGRP is the total number of ply groups in an independent zone.

There will be NDZON number of lines under this keyboard.

**Note:** *INDZON key word card must precede *PLYGRP key word card.

*NODGRP

The above keyword is used to specify the total number of node groups.  A node group used to identify the common independent zone and the common layer group for all the nodes in a group.  The general format is:
*NODGRP
        NGRP
where NGRP is the total number of node groups.

*PLIES
The keyword PLIES is used to specify the maximum number of plies that exists in an independent zone.  The general input format is:
*PLIES
        INDI(1)                          NMAXPL(1)
        INDI(2)                          NMAXPL(2)
        INDI(3)                          NMAXPL(3)
        .                                .
        .                                .
        .                                .
        INDI(n)                          NMAXPL(n)

where INDI is the independent zone No., and NMAXPL is the maximum number of plies in  an independent zone.  The maximum number of plies for all the independent zones must be defined.
**Note:** *INDZON key word card must precede *PLIES key word card.

*MATSYS
The keyword MATSYS is used to specify the total number of material systems in a structure.  The general input format is:
*MATSYS
        NMAT
where NMAT is the total number of material systems in a structure.

*ORISYS
The keyword ORISYS is used to specify the total number of orientation systems in a structure.  The general input format is:
*ORISYS
        NORI

where NORI is the maximum number of orientation systems in a structure.

*THKSYS

The keyword THKSYS is used to specify the total number of thickness systems in a structure. The general input format is:

*THKSYS
        NTHK

where NTHK is the total number of thickness systems in a structure.

*RNDGRP

This key word is used to specify the maximum number of random field groups related to material properties for each independent zone in a structure.

The general input format is:

*RNDGRP
        INDI(1)           NRFT(1)
        INDI(2)           NRFT(2)
        INDI(3)           NRFT(3)
        INDI(n)           NRFT(n)

where INDI is the independent zone number NRFT is the total number of random field groups (*CORTAB) related to the constituent material properties in an independent zone.

The number of random field groups related to the constituent material properties for all the independent zones must be defined.

**Note:** *INDZON key word card must precede *RNDGRP card.

*RANTEM

This key word is used to specify the maximum number of random variables related thermal loads and corresponding number of perturbation sets.

The general input format is:

*RANTEM
        NRTEM                   NTPER

where NRTEM is the number of temperature related random variables and NRPER is the total number of perturbations related to the temperature related random variables.

The number of random variables related to the temperatures for all the independent zones must be defined.

*END

This key word card is always required to terminate the parameter data block input. It must always be put at the very end of parameter data input block. The general input format is

        *END

## A.3.1.2 Material Property Uncertainty Model Input Data Group:

*NODGRP

The keyword NODGRP is used to specify the node numbers that belong to a specific ply group of a specific independent zone. The general input format is shown below:

    *NODGRP
    IG
    NODB(IG)    NODE(IG)    INDZ(IG)    ILAY(IG)
    where   IG        is the node group number
            NODB(IG)     is the beginning node number of a series of nodes in group IG,
            NODE(IG)     is the end node number of a series of nodes in group IG,
            ILAY(IG)     is the ply group number to which NODB(IG) through NODE(IG)
                         belongs
            INDZ(IG)     is the independent zone number to which NODB(IG) through
                         NODE(IG) belongs

Remember that the node groups for all the ply groups and all the independent zones must be specified.


*RESTAB

The keyword RESTAB is used to specify the plies and their responses for which the probabilistic simulation is desired. The response table for all the plies within an independent zone must be specified. The code used to specify the computational request is 0(zero) or 1(one). 0 means the probabilistic ply response computation is not desired and 1 means the probabilistic ply response computation is desired. The general input format is:

    *RESTAB
    IZ
    NPB, NPE
    IEX(1) IEXE(2) … (EX(23)
    where
            IZ               is the independent zone number
            NPB    is the beginning ply number of independent zone IZ
            NPE    is the end ply number of independent zone IZ
            IXE(I) is the code to request $i^{th}$ probabilistic ply response
    Following is the list of ply responses for which the probabilistic analysis can be
    performed.
 1 Longitudinal strain
 2 Transverse strain
 3 Shear strain
 4 Longitudinal stress
 5 Transverse stress
 6 Shear stress

 7 Longitudinal tensile strength
 8 Longitudinal compressive strength
 9 Transverse tensile strength
 10 Transverse compressive strength
 11 Shear strength

12 Modified distortion energy failure criterion
13 Hoffman's failure criterion
14 Interply delamination failure criterion

15 Fiber crushing criterion  (compressive strength)
16 Delamination criterion  (compressive strength)
17 Fiber micro buckling criterion  (compressive strength)

18 Failure in longitudinal direction
19 Failure in transverse direction
20 Failure in Shear strength

21 Out of plane Shear 13
22 Out of plane Shear 23
23 Sigma zz

*PLYTAB
        The keyword PLYTAB is used to specify the ply configuration of a laminate in a ply
group of any independent zone.  The ply configuration of a laminate is specified by the existence
of a ply. The code used to specify the existence is 0(zero) or 1(one).  0 means the ply does not
exists and 1 means the ply exists.  The general input format is:

        *PLYTAB
        IZ,  LG,
        NPL(1,IZ,LG),  NPL(2,IZ,LG),  ...  NPL(NMAXPL(IZ),IZ,LG)
        where
                IZ                 is the independent zone number
                LG                 is the ply group number of independent zone IZ
                NMAXPL(IZ) is the maximum number of plies in an indpendent zone IZ
                NPL                is the ply existence code, either 0 or 1.  Code zero indicates that
                                   the ply does not exist and 1 indicates that the ply exists

*MATSYS
        The keyword MATSYS is used to specify the uncertainties of a specific material.  The
general input format is:
        *MATSYS
        I
        'KEY(I)KEYS(I)'    FVRM(I)    VVRM(I)    FRS(I)    FVRMS(I)    VVRMS(I)
        C(1,I)  C(2,I)  C(3,I)  ...        C(29,I)
        CF(I), CVV(I), CFRS(I), CFS(I), CVVS(I)
        CS(1,I)CS(2,I)CS(3,I)...        CS(29,I)
        IM(1,I)IM(2,I)IM(3,I)...        IM(29,I)
        IF(I), IV(I), IFR(I), IFS(I), IVS(I)
        IMS(1,I)        IMS(2,I)        IMS(3,I)        ...        IMS(29,I)

where I is the material system number KEY(I)  and KEYS(I) are the acronyms defining the I th primary and secondary composite material system .  The acronym must be specified in quotes (').  The acronym is used to pull the mean values of composite material properties from the data bank.  Refer to Table 3.4.1.1 and Table 3.4.1.2 of the IPACS manual for the description of composite material acronyms.  FVRM(I), VVRM(I), FRS(I), FVRMS(I), and VVRMS(I) are mean values of the primary system fiber volume ratio, the primary system void volume ratio, fraction of secondary system,  the secondary system fiber volume ratio and the secondary system void volume ratio respectively of the I th material system.  C(n,I) is the coefficient of variation for the $n^{th}$ primary material property random field of the I th material system.  The list of the random field numbers is given in section 3.5 of IPACS manual.  CF(I), CVV(I), CFRS(I), CFS(I), CVVS(I) are the coefficient of variation for the primary system fiber volume ratio, the primary system void volume ratio, fraction of secondary system,  the secondary system fiber volume ratio and the secondary system void volume ratio respectively of the I th material system. IM(n,I) is the distribution type for the n-th material property random field number of I th primary material system.  IF(I), IV(I), IFR(I), IFS(I), IVS(I) are the distribution types for the primary system fiber volume ratio, the primary system void volume ratio, fraction of secondary system, the secondary system fiber volume ratio and the secondary system void volume ratio respectively of the I th material system.

IMS(n,I) is the distribution types for the $n^{th}$ secondary system material property number.  No more than ten integer numbers and eight real numbers in a given line can be specified.  If there are more numbers for a particular data type, then their input should continue in the subsequent lines.

*ORISYS

The keyword ORISYS is used to specify uncertainties of the ply orientations.  The general input format is:

        *ORISYS
                OM(1) OM(2) ...        OM(NORI)
                OC(1)  OC(2)  ...       OC(NORI)
                IO(1)   IO(2)   ...       IO(NORI)

where OM(i), OC(i) and IO(i) are the mean, a constant to specify standard deviation (standard deviation = 90 x constant), and the distribution type respectively of the $i^{th}$ orientation angle system.  NORI is the total number of orientation systems.

*THKSYS

The keyword THKSYS is used to specify uncertainties of the ply thickness.  The general input format is:

        *THKSYS
                TM(1) TM(2) ...        TM(NTHK)
                TC(1)  TC(2)  ...       TC(NTHK)
                IT(1)   IT(2)   ...       IT(NTHK)

where TM(i), TC(i) and IT(i) are the mean, the coefficient of variation and distribution type respectively of the $i^{th}$ thickness system.  NORI is the total number of orientation systems. NTHK is the total number of thickness systems.

*MATTAB

The keyword MATTAB is used to specify the material of each ply of a laminate in an independent zone. The material property uncertainty specification of a ply in an independent zone corresponds to a material system id. All the plies of an independent zone must have a material system id defined, and the material property uncertainty for that id must also be defined in

*MATSYS card. The general input format is:

        *MATTAB
        IZ
        NMT(IZ,1)    NMT(IZ,2)    NMT(IZ,3) ... NMT(IZ,NMAXPL(IZ))
        where IZ is the independent zone number. NMT(IZ,n) is the material system number of the $n^{th}$ ply of independent zone IZ, and NMAXPL(IZ) is the maximum number of plies in independent zone IZ.

*ORITAB

The keyword ORITAB is used to specify the uncertainties of each ply orientation of a laminate in an independent zone. The orientation uncertainty specification of a ply in an independent zone corresponds to an orientation system id. All the plies of an independent zone must have an orientation system id defined, and the orientation uncertainty for that id must also be defined in

*ORISYS card. The general input format is:

        *ORITAB
        IZ
        NOT(IZ,1)    NOT(IZ,2)    NOT(IZ,3) ... NOT(IZ,NMAXPL(IZ))
        where IZ is the independent zone number, NOT(IZ,n) is the orientation system number of the $n^{th}$ ply of independent zone IZ, and NMAXPL(IZ) is the maximum number of plies in independent zone IZ.

*THKTAB

The keyword THKTAB is used to specify the uncertainties of each ply thickness of a laminate in an independent zone. The thickness uncertainty specification of a ply in an independent zone corresponds to a thickness system id. All the plies of an independent zone must have a thickness system id defined, and the thickness uncertainty for that id must also be defined in

*THKSYS card. The general input format is

        *THKTAB
        IZ
        NTT(IZ,1)    NTT(IZ,2)    NTT(IZ,3) ... NTT(IZ,NMAXPL(IZ))
        where IZ is the independent zone number and NTT(IZ,n) is the thickness system number of $n^{th}$ ply of independent zone IZ, and NMAXPL(IZ) is the maximum number of plies in independent zone IZ.

*CORTAB

This key word is used only in case of a primitive variable based method to specify the correlation of a particular random field between different plies (correlation table) of a composite material. Refer to Appendix A for the definition of a correlation table. The general input format for the primitive variable based method is:

*CORTAB
IZ
NRFi          NRFj
ICOR(1)       ICOR(2) ...     ICOR (NMAXPL(IZ))


Where IZ      is the independent zone number
NRFi          is the beginning material related random field number.      NRFj is the
              end material related random field number (Legal list of material related
              random field numbers are given in Appendix A, Section A.3).
ICOR(i)       is the correlation id number for the i$^{th}$ ply  0<= ICOR(i) <=NMAXPL(IZ)
NMAXPL(IZ)    is the maximum number of plies in independent zone, IZ.

The cards (NRFi  NRFj) and (ICOR(1), ... ,ICOR(NMAXPL(IZ)) can be repeated for additional random fields in independent zone, IZ. For additional independent zones the data should be specified in the same order discussed above.

Remember that the correlation table for all the material related random fields of all the independent zones should be specified. The random field automatically becomes deterministic if its correlation table is not defined.


*MEANTM

This key word is used to specify mean ply temperatures at different nodes. The temperature groups and the number of node groups must be exactly same. The correlated temperatures at different nodes can be specified using the *RELPER card. The standard deviations for the temperatures are specified in the *STDVTM card. The first ply is the bottom ply based on the local z-definition. The general input format for the definition of the mean ply temperatures is:

*MEANTM
NODi          NODj

PT1    PT2    …       PTn

NODi  is the beginning ply number.
NRFj   is the last node number in a group.
PTi  is the mean i$^{th}$ ply temperature
The cards (NODi  NODj) and (PT1, ... ,PTn) can be repeated for additional nodes.


*STDVTM

This key word is used to specify standard deviation of the ply temperatures at different nodes. The temperature groups and the number of node groups must be exactly same. The first ply is the bottom ply based on the local z-definition. The general input format for the definition of the ply temperature standard deviation is:

*STDVTM
NODi          NODj

PSTD1         PSTD2         …       PSTDn

NODi  is the beginning ply number.
NRFj   is the last node number in a group.
PSTDi  is the [ith] ply temperature standard deviation
The cards (NODi  NODj) and (PSTD1, ... ,PSTDn) can be repeated for additional nodes.

*RELPER

This key word is used to specify the autocorrelation matrix for random temperature variables.  Basically, it represents the eigen-vectors of the correlation matrix.  The general input format for the definition of the ply temperature standard deviation is:

*RELPER
NR
NODi          NODj
EG1           EG2    …       EGn

NODi  is the beginning ply number.
NRFj   is the end lst ply number.
EGi  is the ith ply autocorrelation coefficient
The cards (NODi  NODj) and (EG1, ... ,EGn) can be repeated for additional nodes.

*IRVPER

This key word is used to specify the perturbation of particular temperature random variables.  Any random variable can be perturbed for any number of times.  It also signifies in what order the variables shall be perturbed.  Input entry in this card must be used in conjunction with the *ABSPER card which specifies the corresponding perturbation magnitude.  Basically, it represents the eigen-vectors of the correlation matrix.  The general input format for the definition of the temperature random variables perturbation definition is:

*IRVPER
NP(1)  NP(2) … NP(n)

where NP(i) represents the ith perturbation of random variable NP(i).
The cards (NPi  NPn) can be repeated for additional variable perturbations.

*ABSPER

This key word is used in conjunction with the *IRVPER input card.  It is used to specify the magnitude of the perturbation for the corresponding random variable in the *IRVPER card. The general input format for the definition of the perturbation magnitude is:

    *ABSPER
    PV(1)  PV(2) … PV(n)

where PV(i) represents the mangitude of the $i^{th}$ perturbation of random variable NP(i) specified in *IRVPER card.
    The cards (PVi  PVn) can be repeated for additional variable perturbations.

*REFTEM

This key word is used to specify the reference temperature of the material.  The general input format for the definition of the reference temperature is:

    *REFTEM
    IZ
    REFTM

where IZ represents the independent zone and the REFTEM the reference temperature in $^{o}$F units.  The cards IZ and REFTM can be repeated for additional independent zones.

**A.3.2 Input for Probabilistic Output Request:**

This section of input always begins with $FPI card.  The response locations on the structure and the type of probabilistic analysis are defined in this section of input.  The input details are given in the following card:
    *STRU
    ISTAT NTYPE NODN IDUMP IDUMP NCOMP
    where
        ISTAT   = 1 for the Static Analysis
                = 2 for the Buckling Analysis
                = 3 for the Frequency Analysis
        NTYPE   = 1 for Displacement Response
                = 2 for Ply Strain/Stress Response
        NODN    Node Number where probabilistic output is requested
        IDUMP   Reserved for future use
        NCOMP   displacement or stress/strain component in static analysis
                    mode number in case of buckling or frequency analysis

### A.3.3 IPACS Execution Control Input:

The input to this section always begins with $EXE2 card.  The IPACS execution control is defined in this section.  The input to this section is as follows:
    IX1 IX2 IX3 IX4 IX5

where the variables IX1, IX2, IX3, IX4 and IX5 could be either 0 (zero) or 1.  0 means suppress the execution of the analysis type discussed below.  1 means perform the analysis.
    IX1  = 1 Compute the perturbed material properties at every scale.
    IX2  = 1 Prepare the input file for the probabilistic finite element analysis.
    IX3  = 1 Perform the probabilistic finite element analysis.
    IX4  = 1 Extract desired structural responses as indicated in $FPI section.
    IX5  = 1 Compute the CDF of desired structural responses

### A.3.4 Output

The user generally controls IPACS output.  However, by default IPACS provides minimum necessary output required for the probabilistic assessment of composite structure.  The minimum output consists of the following: (i) an echo of the input, (ii) CDF of the material properties and the desired structural response, (iii) the sensitivity factors of the primitive variables for the material properties and the desired structural response.  The important output files are xxx21.fpimov, xxx21.nesout and xxx21.rantab.  The names of these files and their respective contents are listed in Table A.3.4.1, on the next page.

Several other output files are created at intermediate computation stage or at the end of the computations.  Some of these files provide an interface between different modules or serve as a database system.  These files contain information for the user to study the overall problem behavior in greater detail.

## Table A.3.4.1  List of Output Files

jn  -   jobname
IZ   -   Independent Zone No.
LG  -   Ply Group No.
IPM  -  Method No.
$$  -   A unique job number assigned by the computer

| File Name | File Contents |
|---|---|
| jn.msp-IZ-LG | Mean value and standard deviations for ply material properties. |
| jn.cpp-IZ-LG | CDF of ply material properties |
| jn.cpl-IZ-LG | CDF of laminate material properties |
| jn-IZ-LG-IPM-IC.PIC | If IC = 0 Mean Values of material properties. Perturbations of A, C, and D matrices terms for primitive variable based method |
| jn-IZ-IPM.dat | Data required for finite element analysis. The file contains the data supplied by the user and that generated by the program |
| jn-IZ-IPM.pdb | Perturbation database. |
| jn-IZ-IPM.datu | Perturbation data for each desired response. |
| jn-IZ-IPM.dist | Statistics of Primitive Variables for each independent zone. |
| jn-IPM.datu | FPI input file. |
| jn-IPM.dist | Statistics of primitive variables required for the probabilistic analysis of structural response. |
| jn-IPM.fpinp | Input file prepared by program to perform fast probability integration. |
| jn-IPM.fpimov | Sensitivity factors of primitive variables at cumulative probability levels of 0.001 and 0.999. |
| jn-IPM.fpibin | FPI logfile |
| jn-IPM.nesout | Discretized CDF of a structural response. |
| jn-IZ-IPM.out | Echo of FEM input and Results of Unperturbed Solution. |
| jn-IBM.FPIMOV | Sensitivity factors for independent random variables at probability levels 0.001 and 0.999. |

## SAMPLE INPUT FILE:

```
CFEM
$PIC1
*INDZON
        1
*NODGRP
        1
*PROSOL
       21
*PLYGRP
    1   1
*PLIES
    1   8
*RNDGRP
    1   2
*MATSYS
        1
*ORISYS
        4
*THKSYS
        1
*RANTEM
        1        4
*END
*NODGRP
        1
        1        9        1        1
*RESTAB
        1
        1        8
c    o-skip  fpi       1-with fpi
        0        0        0        1        1        0        0        0        0        0
        0        0        0        0        0        0        0        0        0        0
        0        0        0
*PLYTAB
        1        1
        1        1        1        1        1        1        1        1
*MATSYS
        1
'AS--EPOXAS--EPOX'   0.60    0.02     0.000001   0.60  0.02
     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
     0.05     0.05     0.05     0.05     0.05
     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
        2        2        2        2        2        2        2        2        2        2
        2        2        2        2        2        1        1        2        2        2
        2        2        2        2        1        1        1        2        2
        2        2        2        2        2
        2        2        2        2        2        2        2        2        2        2
        2        2        2        2        2        1        1        2        2        2
        2        2        2        2        1        1        1        2        2
*MATTAB
        1
        1        1        1        1        1        1        1        1
*ORISYS
    -45.0      0.0     45.0     90.0
     0.02     0.02     0.02     0.02
        2        2        2        2
*ORITAB
        1
        3        1        2        4        4        2        1        3
```

```
*THKSYS
   0.020
   0.050
      2
*THKTAB
      1
      1         1         1         1         1         1         1         1
*CORTAB
      1
      1         1
      1         1         1         1         1         1         1         1
     33        33
      1         1         1         1         1         1         1         1
*MEANTM
      1         9
   200.0     200.0     200.0     200.0     200.0     200.0     200.0     200.0
*STDVTM
      1         9
    10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
*RELPER
      1
      1         9
     1.0       1.0       1.0       1.0       1.0       1.0       1.0       1.0
*IRVPER
      1         1         1         1
*ABSPER
    -2.0      -1.0       1.0       2.0
*END
$NES
*FEM
*DISP
*FORC 1
*ELEM 4
   75
*COMPOSITE
*TEMP
*PERT
*NODES 9
*BOUN 18
*CONS 0
*PRIN
*END
*INC
    0
*ITER
    100    0.0001    0.0001    0.0001    0.0001
*COOR
      1     0.000     0.000     0.000     1.0
      2     1.000     0.000     0.000     1.0
      3     2.000     0.000     0.000     1.0
      4     0.000     1.000     0.000     1.0
      5     1.000     1.000     0.000     1.0
      6     2.000     1.000     0.000     1.0
      7     0.000     2.000     0.000     1.0
      8     1.000     2.000     0.000     1.0
      9     2.000     2.000     0.000     1.0
*ELEM     75
      1     1     2     5     4
      2     2     3     6     5
      3     4     5     8     7
      4     5     6     9     8
*BOUN
      1     1     0
      4     1     0
      7     1     0
      1     2     0
      4     2     0
```

```
    7    2    0
    1    3    0
    4    3    0
    7    3    0
    1    4    0
    4    4    0
    7    4    0
    1    5    0
    4    5    0
    7    5    0
    1    6    0
    4    6    0
    7    6    0
*FORC
    5    3  1000.0
*ORIEN
    1    9  1.00   0.00   0.00
    1    9  0.00   0.00   1.00
C*LAMI
INCLUDE
*PRINTOPTION
 REACTION
 STRESS
 STRAIN
 TOTALDISPLACEMENT
*END
$RAN
*DEFI    1
 1000.0   100.0    2
 FORCE
    5    3    1.0
$FPI
*STRU
    1    1    5    0    0    3
$EXE2
    1    1    1    1    1
```

APPENDIX B:

The probabilistic stress, frequency and buckling analysis for a typical engine structure was created and the analysis was performed. The probabilistic analysis of an engine fan, high-pressure compressor blades was performed using the integrated EST/BEST software system. The uncertainties assumed for the blade are listed in the Table I. Figure 1 shows the cumulative distribution (CDF) of the total displacement at the tip of the blade. Figure 2a and Figure 2b shows the sensitivity of the total displacement to the primitive variables. The sensitivity of the displacement is controlled by the length, modulus, thickness, temperature and coefficient of thermal expansion at probability level of 0.001 whereas modulus controls at the probability of 0.999. Figure 3 shows the CDF of the first natural frequency and figure 4 shows its sensitivity to the primitive variables. The scatter of the frequency range between 900 to 1280 cps. The natural frequency of the high-pressure compressor (HPC) blade is found to be sensitive to the modulus, thickness and mass density at probability level of 0.001 whereas the order of sensitivity changes to mass density, modulus and thickness at probability level of 0.999. Figure 5 and figure 6 shows the CDF and sensitivity of the critical buckling load for the HPC blade stage 4. The modulus and the thickness dominate the critical buckling load at all probability levels. Thus, the critical load is thus controlled by the stiffness.

## Table I.  Primitive variable uncertainties used for the engine blade

| Fan Blade Stage 1 (Stress analysis) | | |
|---|---|---|
| Variable | Scatter (%) | Distribution |
| Temperature | 10.0 | Normal |
| Length | 4.0 | Log Normal |
| Thickness | 2.5 | Log Normal |
| Modulus of Elasticity | 7.0 | Weibull |
| Coefficient of thermal Expansion | 7.0 | Normal |
| High pressure compressor Stage 2 (Frequency analysis) | | |
| Length | 4.0 | Log Normal |
| Thickness | 2.5 | Log Normal |
| Modulus of Elasticity | 7.0 | Weibull |
| Mass density | 7.0 | Normal |
| High pressure compressor Stage 4 (Buckling analysis) | | |
| Length | 4.0 | Log Normal |
| Thickness | 2.5 | Log Normal |
| Modulus of Elasticity | 7.0 | Weibull |
| Poisson's ratio | 5.0 | Weibull |
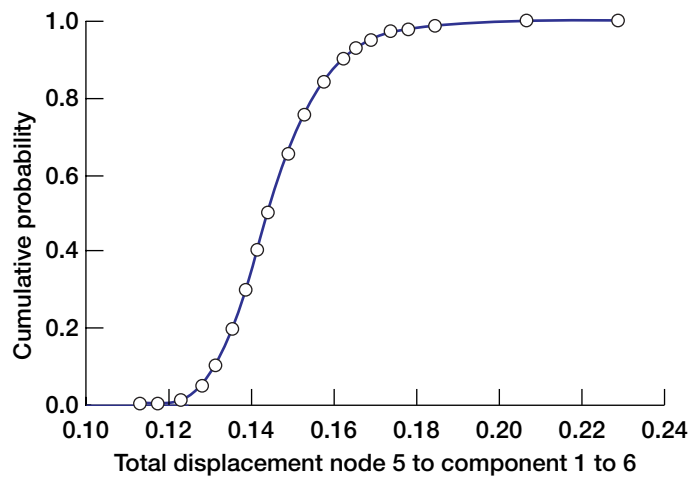
Figure 1.—Cumulative distribution function of the total
displacement at the tip of the blade stage 1.



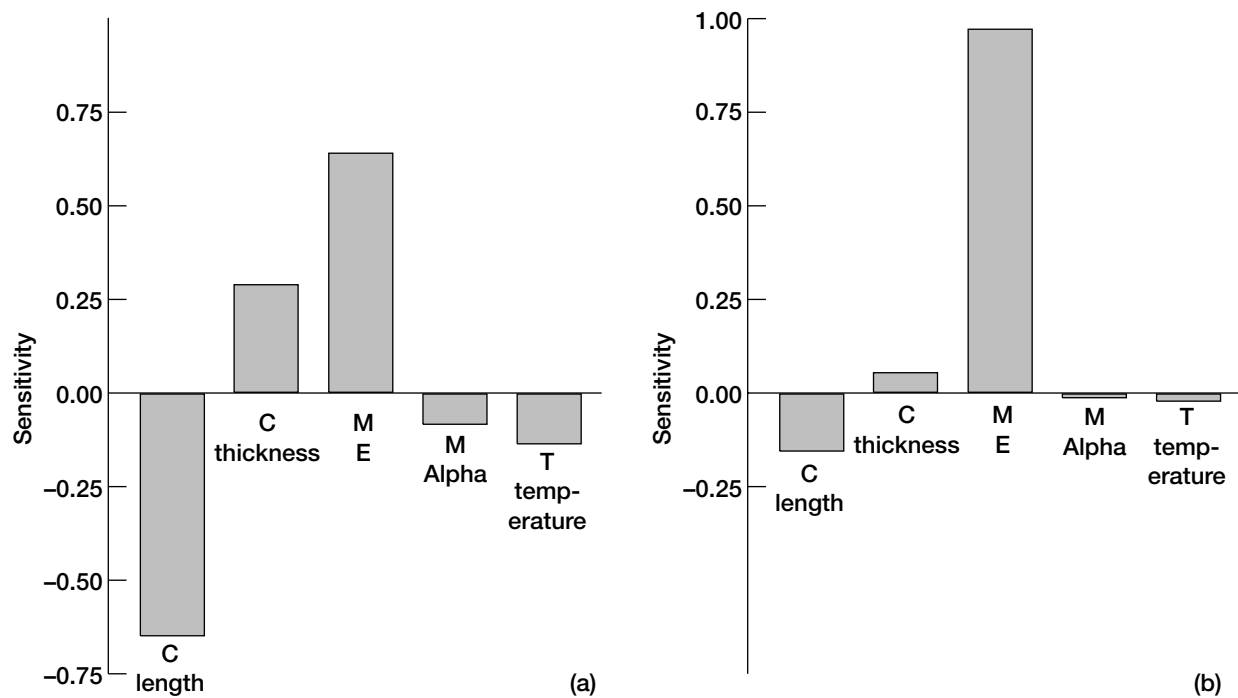Figure 2.—Sensitivity of total displacement at the tip of the fan blade stage 1 to the primitive random variable
for (a) 0.001 probability and (b) 0.999 probability.
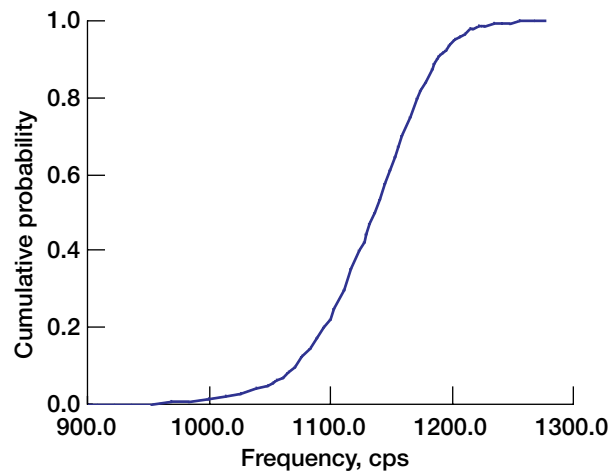
Figure 3.—Cumulative distribution function of the first natural frequency—high pressure compressor blade stage 2.



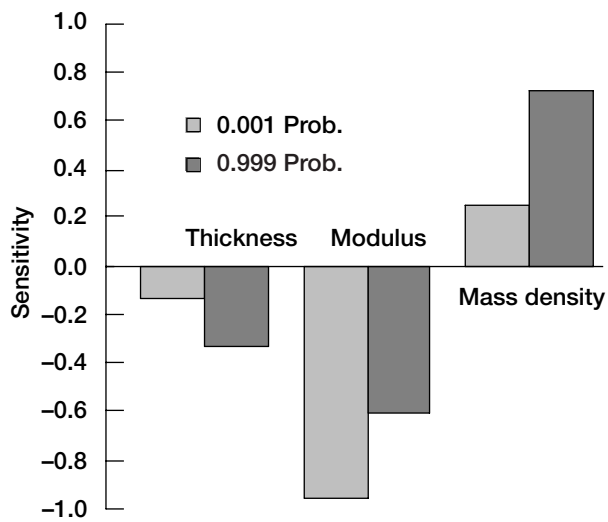Figure 4.—Sensitivity of first natural frequency to the primitive variables—high pressure compressor blade stage 4.
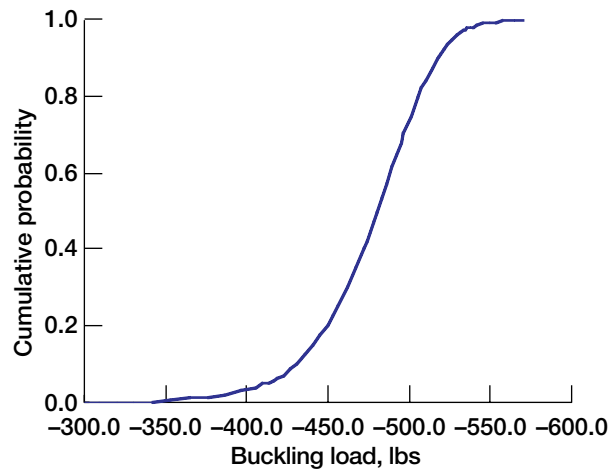
Figure 5.—Cumulative distribution function of the
critical buckling load—high pressure compressor
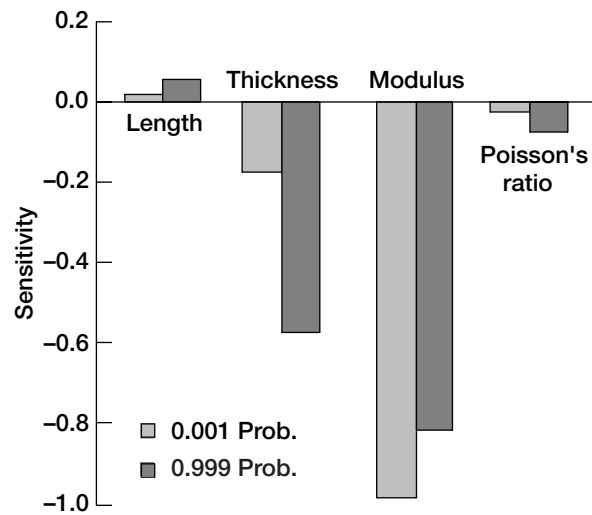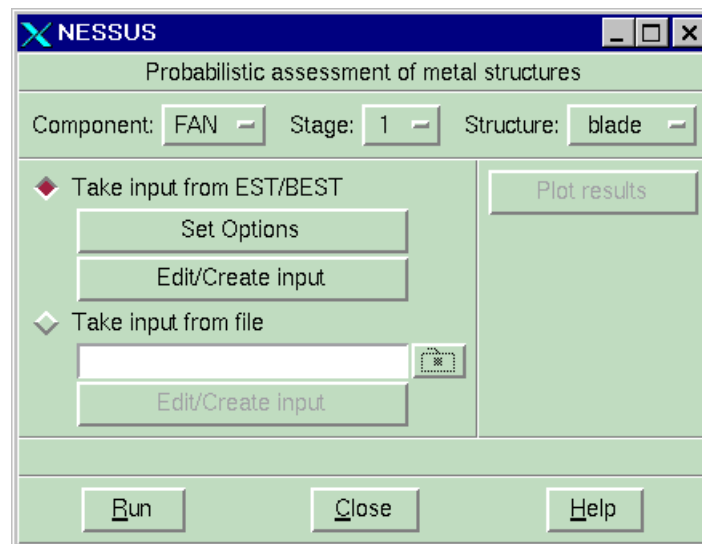blade stage 4.



Figure 6.—Sensitivity of the critical buckling load to
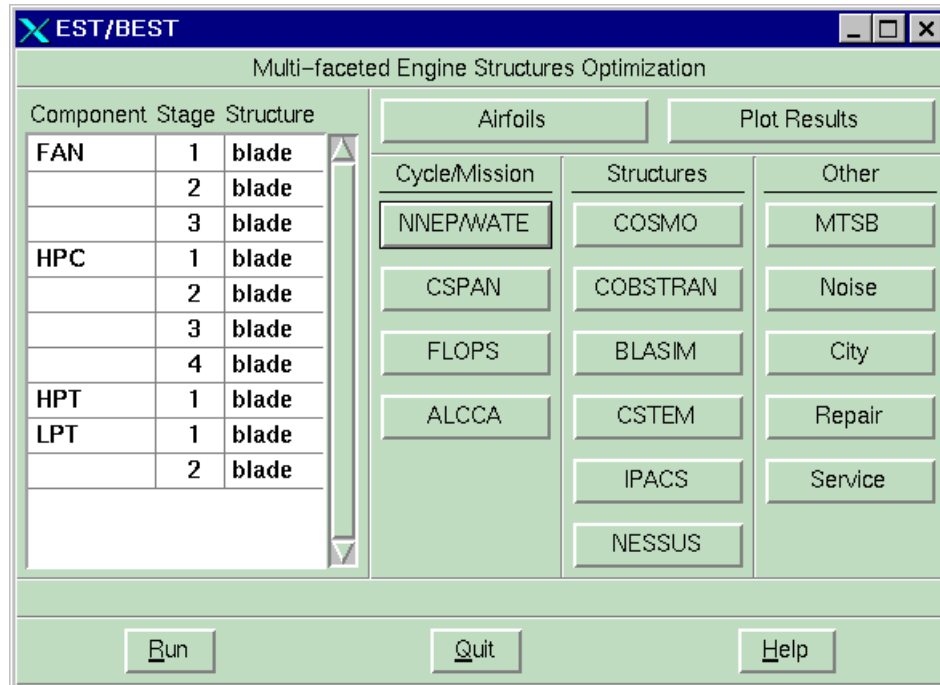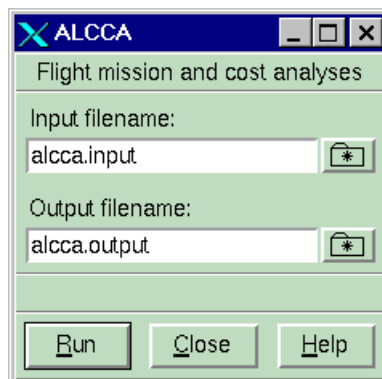the primitive variables—high pressure compressor
blade stage 4.

# APPENDIX C: EST/BEST GRAPHICAL USER INTERFACE SCREENS
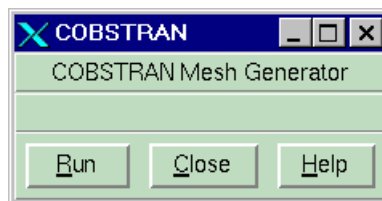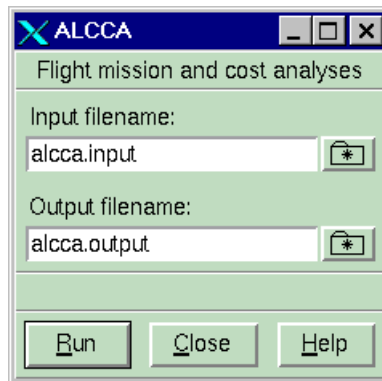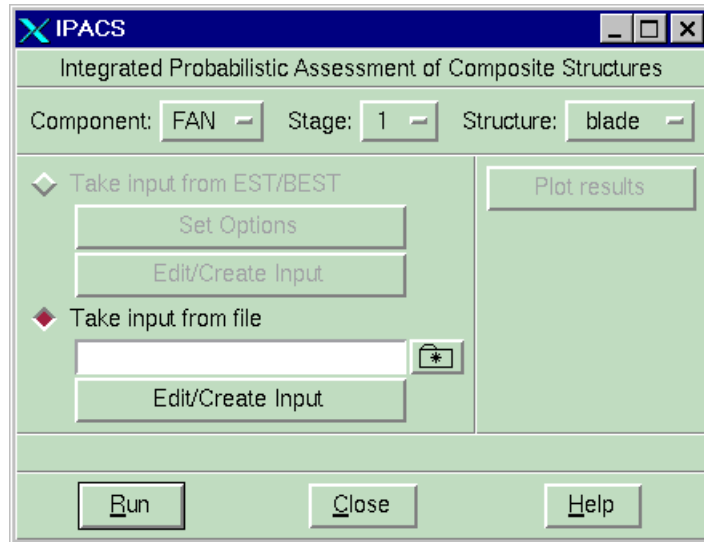
## HPC Stage 1 Blade Options

### Mesh Options

Airfoil: NACA-65D

Element: shell

Chordwise: 4

Spanwise: 10

Plot blade cross sections

### Material Options

◆ Metal

TiAlMn

◇ Composite

Type: PMC   Fiber volume ratio: 

Fibers: AS--   Void volume ratio: 

Matrix: EPOX   Interface thickness: 

Ply Orientation Thickness

1 

Add Ply   Delete Ply

### Analysis Options

Blade impact damage data:

Velocity (knots): 

Object density: 

Object radius: 

Structural analysis module:

◇ CSTEM

◇ IPACS

◆ Take input from EST/BEST

Set Options

Edit/Create Input

◇ Take input from file

Edit/Create Input

◆ NESSUS

◆ Take input from EST/BEST

Set Options

Edit/Create input

◇ Take input from file

Edit/Create input

OK   Cancel   Help

## Airfoils

Display/modify normalized airfoils

Airfoil name: NC65A010

Number of coordinates in upper airfoil: 26

| coordinate | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| X UPPER: | 0.0 | 0.005 | 0.0075 | 0.0125 | 0.025 | 0.05 | 0.075 | 0.1 | 0.15 | 0.2 |
| Y UPPER: | 0.0 | 0.00765 | 0.00928 | 0.01183 | 0.01623 | 0.02182 | 0.0265 | 0.0304 | 0.03658 | 0.04127 |

Number of coordinates in lower airfoil: 26

| coordinate | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| X LOWER: | 0.0 | 0.005 | 0.0075 | 0.0125 | 0.025 | 0.05 | 0.075 | 0.1 | 0.15 | 0.2 |
| Y LOWER: | 0.0 | -0.00765 | -0.00928 | -0.01183 | -0.01623 | -0.02182 | -0.0265 | -0.0304 | -0.03658 | -0.04127 |

Open Existing Airfoil | Update Display of Coordinates | Sort Coordinates by X | Plot Airfoil Coordinates | Save to Database | Reset All Fields to Defaults

Close   Help

Normalized Plot for Airfoil NC65A010

**BLASIM**

Blade impact damage assessment

Component: FAN  Stage: 1

Velocity (knots): [    ]
Object density: [    ]
Object radius: [    ]

Run     Close     Help

**COSMO**

Finite element model generation

Component: FAN  Stage: 1  Structure: blade

Airfoil: NACA-65D
Element: shell
Chordwise: 4
Spanwise: 10

Plot blade cross sections

Run     Close     Help

**FLOPS**

Flight mission and cost analyses

Input filename:
flops.input

Output filename:
flops.output

Run     Close     Help
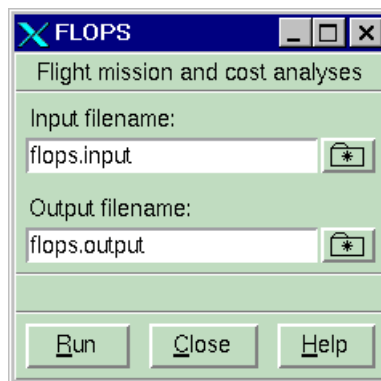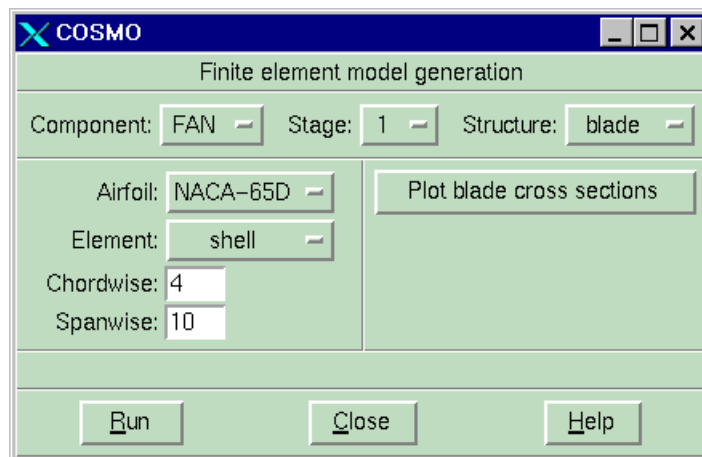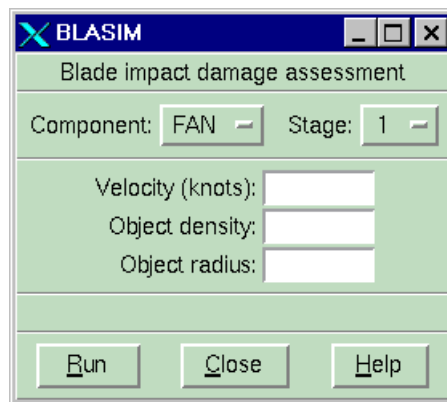
APPENDIX D:          IPACS/COBSTRAN DEMONSTRATION PROBLEMS

   The epoxy-graphite laminate with configuration $(0/45/-45/90)_2$ was used for the blade.  The uncertainties in the constituents such as fiber, matrix, and fabrication variables were considered at the material level.  Pressure loads were considered in the assessment process.  Initially uncertainties in all the material variables were included in the analysis.  However, the significant variables have been listed here for the sake of brevity.  All the uncertainties considered for the probabilistic analysis of a blade are listed in the Table I.  Figure 2a thorough 4a respectively show the cumulative distribution function (CDF) of the longitudinal, transverse and shear stresses at the root of blade for a $0^o$ ply. Correspondingly, the Figures 2b through 4b show their respective sensitivities to the primitive variables.  It is seen that the longitudinal, transverse and shear stresses in the $0^o$ ply at the root are mainly sensitive to the ply thickness indicating the stiffness control. However the transverse and the shear stresses are sensitive to the additional primitive variables such as fiber modulus, matrix modulus and fiber volume ratio.  Similarly Figures 5a through 7a show the CDF of longitudinal, transverse and shear stresses for a $45^o$ ply and Figures 8a through 10a for the $90^o$ ply.  Respective sensitivities are shown in Figures 5b through 10b.  Trends similar to the $0^o$ ply are also observed for the $45^o$ and $90^o$ plies except the fact that matrix modulus and shear modulus participation becomes obvious.  The shear stress in the $90^o$ ply shows stress reversal since it is controlled by the ply mis-alignment.  Nonetheless, the stiffness controls stresses in all the plies.  Therefore, the uncertainties in the thickness as well as ply mis-alignment must be controlled to reduce scatter in the stresses.  Uncertainties in the displacements, ply strains, strengths can also be simulated in an exactly identical manner.

   Figure 11a show the cumulative distribution function of the first natural frequency of the hollow blade and the Figure 11b show its sensitivity to the primitive variables.  The scatter in the frequency is 1000 cps to 1350 cps.  The Fiber modulus, fiber density, matrix density, fiber volume ratio and the ply thickness are the most significant variables to the scatter in the frequency.  The variable sensitivity shows that the stiffness controls at the low probability level, whereas the mass dominates at the higher probability level.

   A distributed point load at the tip of the blade in its axial direction was applied to evaluate the probabilistic buckling analysis.  Figure 12a shows that first critical buckling load scatter range is 5 Lbs. to 18Lbs. (compressive).  The critical load magnitude is quite small since it is controlled by the stiffness as evidenced by sensitivities shown in Figure 12b.  At low probability level the most significant variables are fiber modulus 11, ply thickness and the fiber volume ratio (FVR) whereas the ply thickness, FVR and fiber modulus 11 are sensitive at the high probability level.  Permissible scatter in these variables should be reduced to minimize the scatter in the buckling load.

## Table I.  Primitive variable uncertainties used for the composite engine blade

| Composite Hollow Blade | | |
|---|---|---|
| Variable | Scatter (%) | Distribution |
| Graphite Fiber (AS--): | | |
| Modulus 11 | 7.0 | Weibull |
| Modulus 22 | 7.0 | Weibull |
| Modulus 12 | 8.0 | Log Normal |
| Density | 5.0 | Normal |
| Epoxy matrix (EPOX) | | |
| Modulus | 4.0 | Weibull |
| Density | 5.0 | Log-Normal |
| Fabrication variables | | |
| Fiber volume ratio | 5.0 | Normal |
| Thickness | 6.0 | Log-Normal |
| Ply mis-alignment | 2.0 Degrees | Normal |
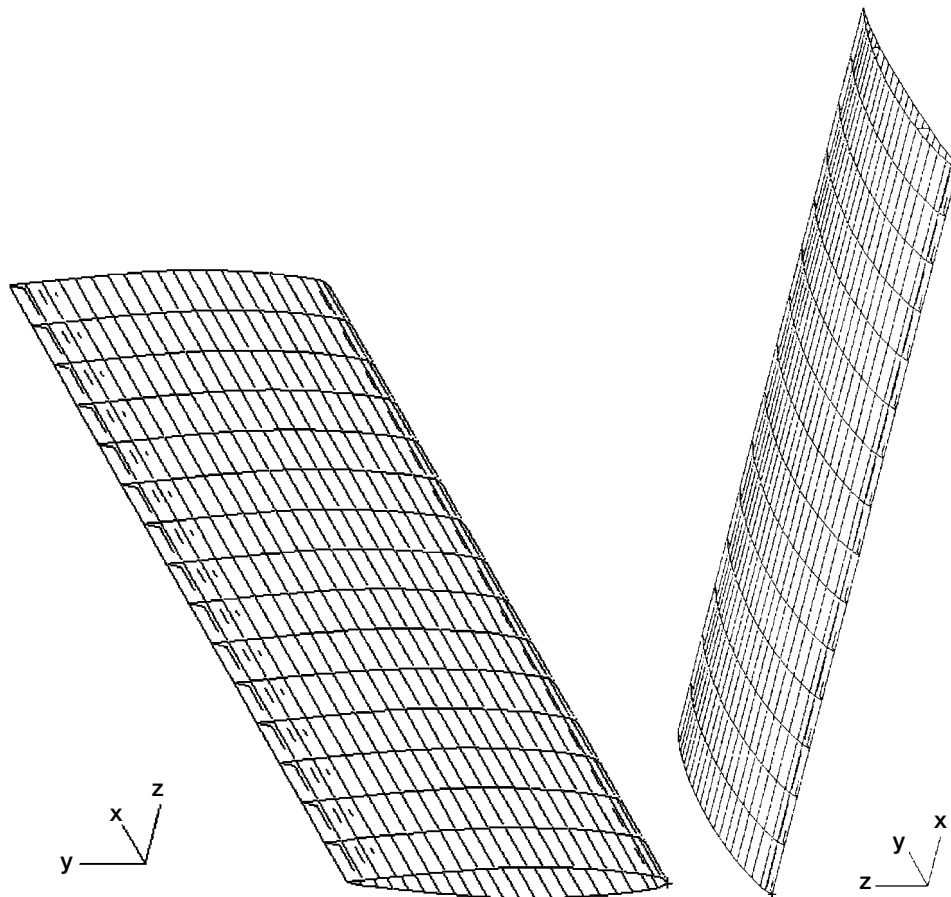


Figure 1.—(a) Finite element model of the hollow engine blade. (b) Finite element model of the hollow engine blade with spars.
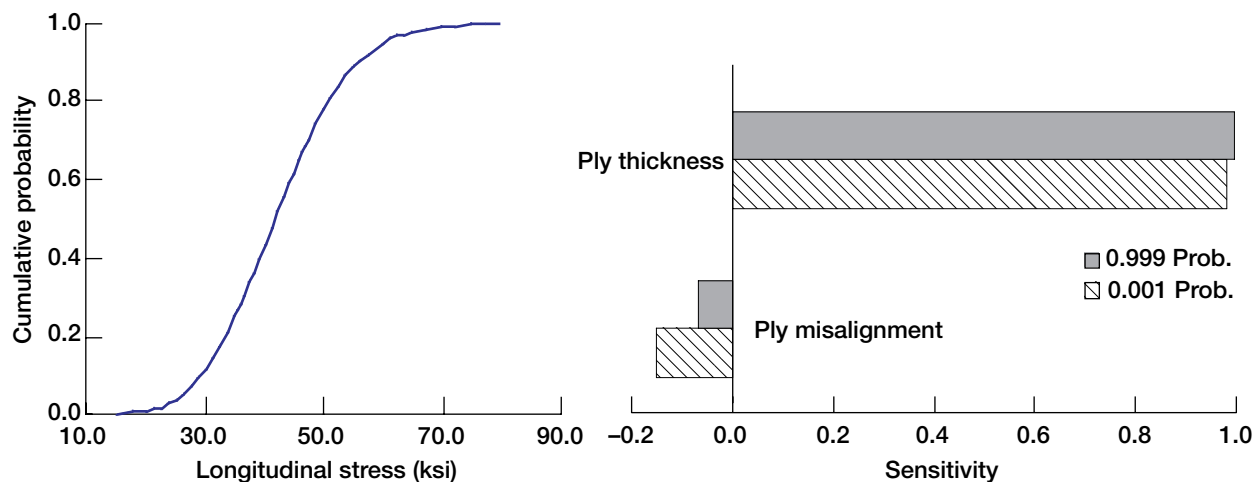
Figure 2.—(a) Cumulative distribution function of the longitudinal stress at root in a 0 degree ply. (b) Sensitivity of longitudinal stress in 0 degree ply at root to the primitive variables
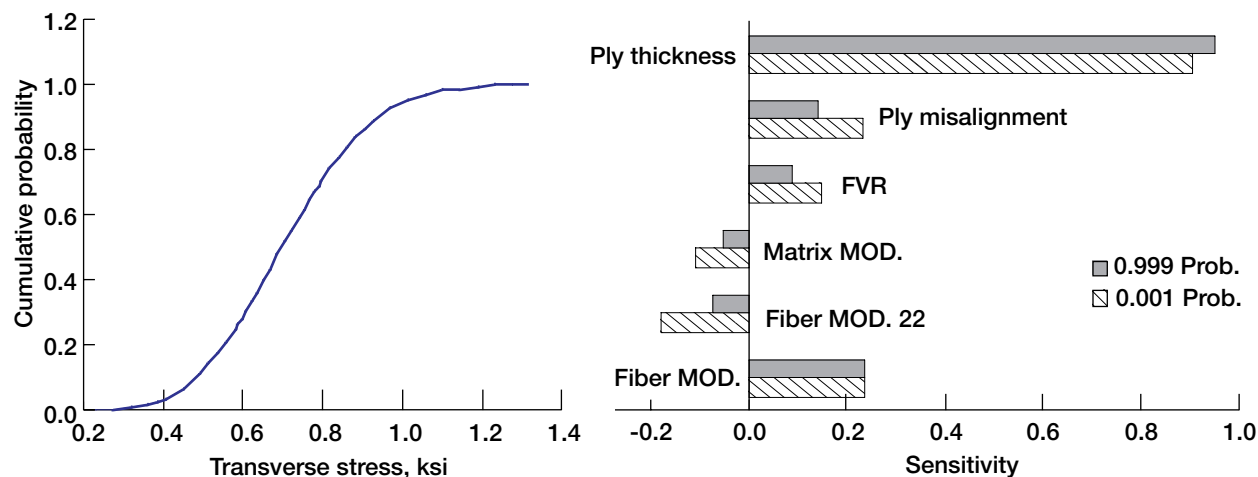


Figure 3.—(a) Cumulative distribution function of the transverse stress at root in a 0 degree ply. (b) Sensitivity of transverse stress in 0 degree ply at root to the primitive variables.
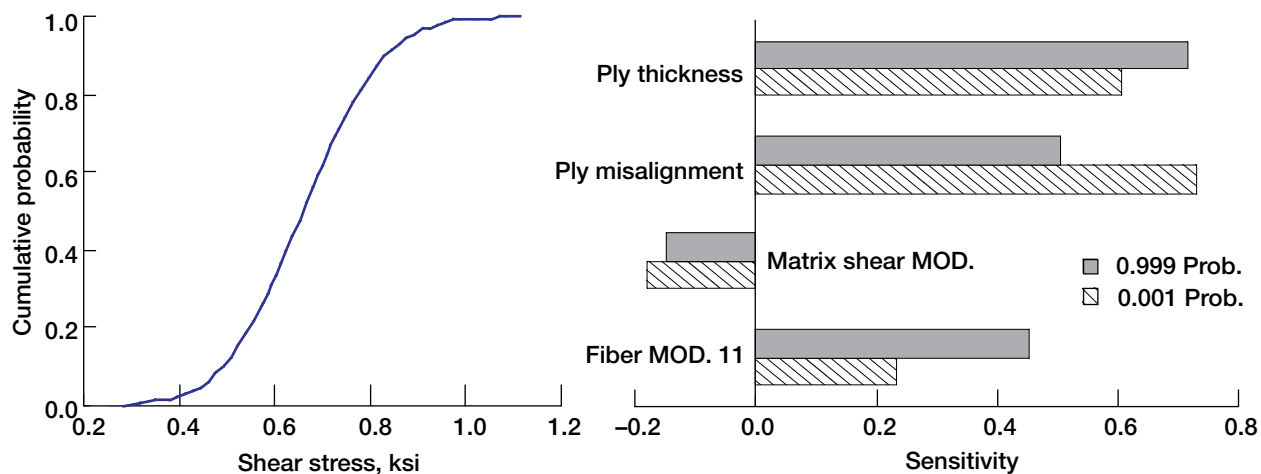
Figure 4.—(a) Cumulative distribution function of the shear stress at root in a 0 degree ply. (b) Sensitivity of shear stress in 0 degree ply at root to the primitive variables.
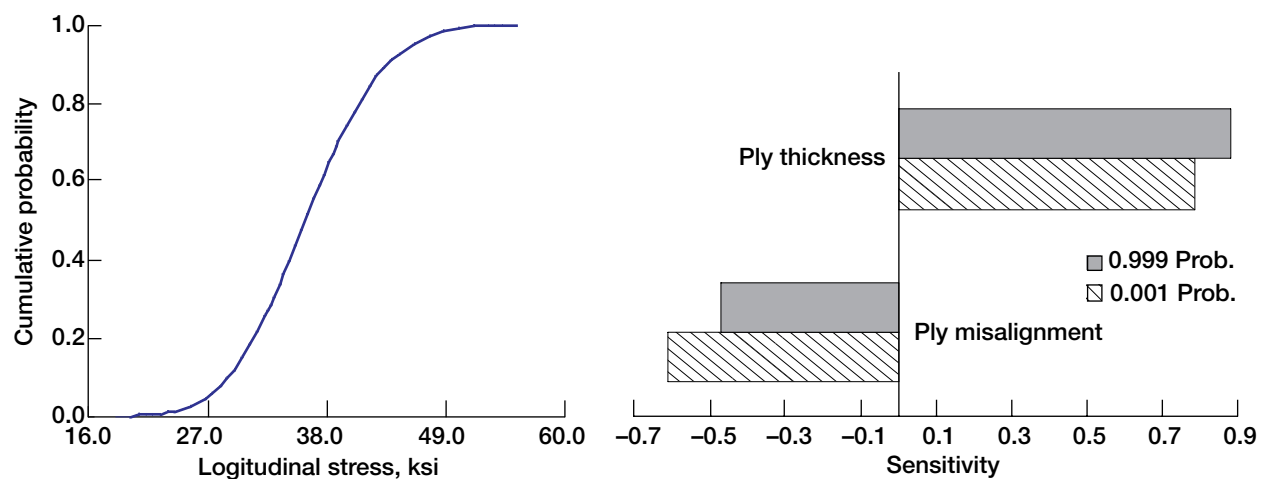


Figure 5.—(a) Cumulative distribution function of the longitudinal stress at root in a 45 degree ply. (b) Sensitivity of longitudinal stress in 45 degree ply at root to the primitive variables.
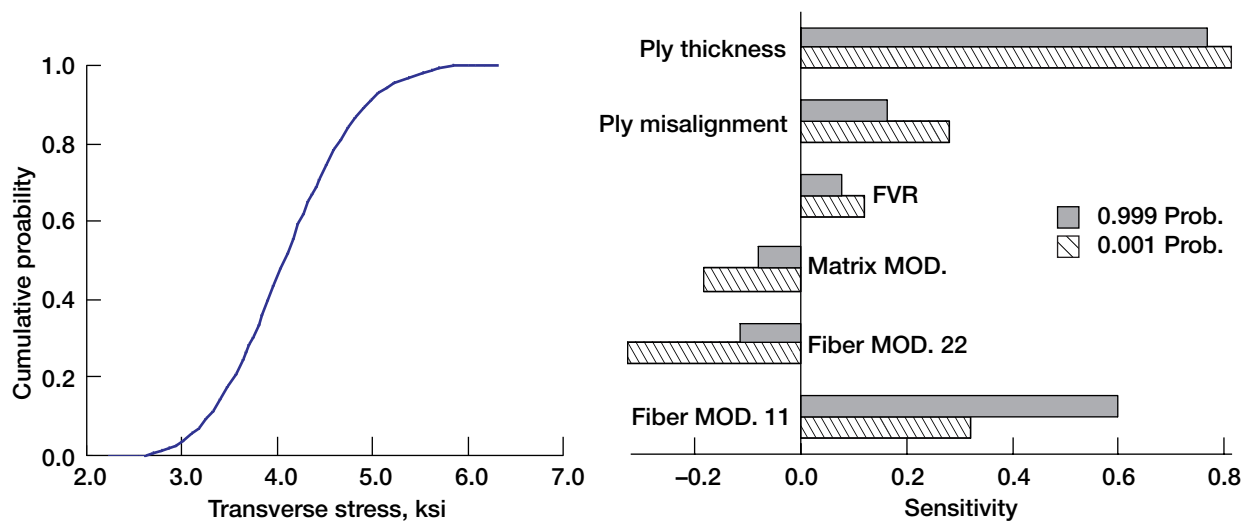
Figure 6(a).—Cumulative distribution function of the transverse stress at root in a 45 degree ply. (b).Sensitivity of transverse stress in 45 degree ply at root to the primitive variables.
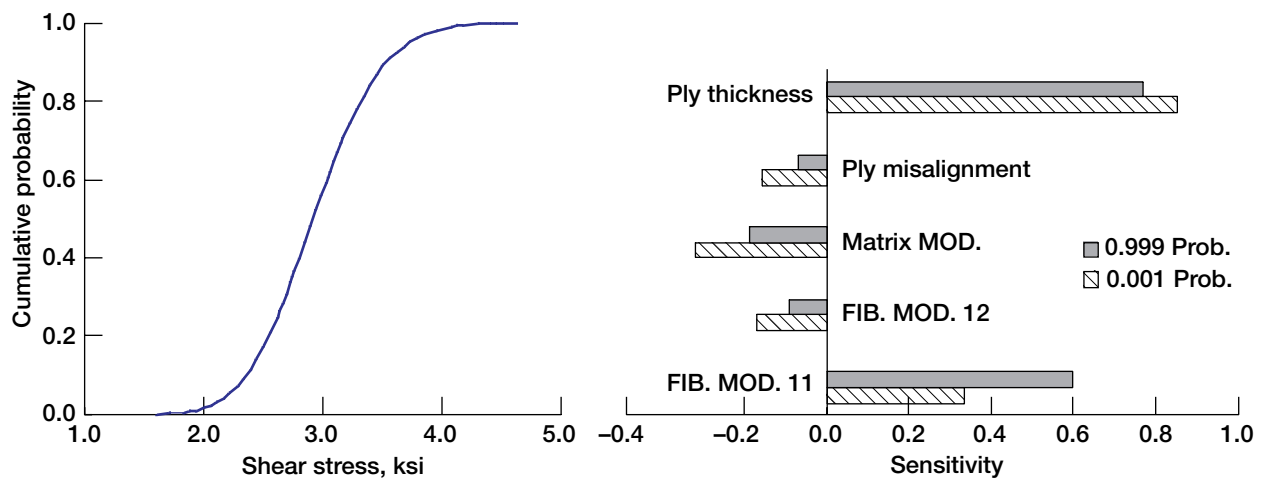


Figure 7.—(a) Cumulative distribution function of the shear stress at root in a 45 degree ply. (b) Sensitivity of shear stress in 45 degree ply at root to the primitive variables.
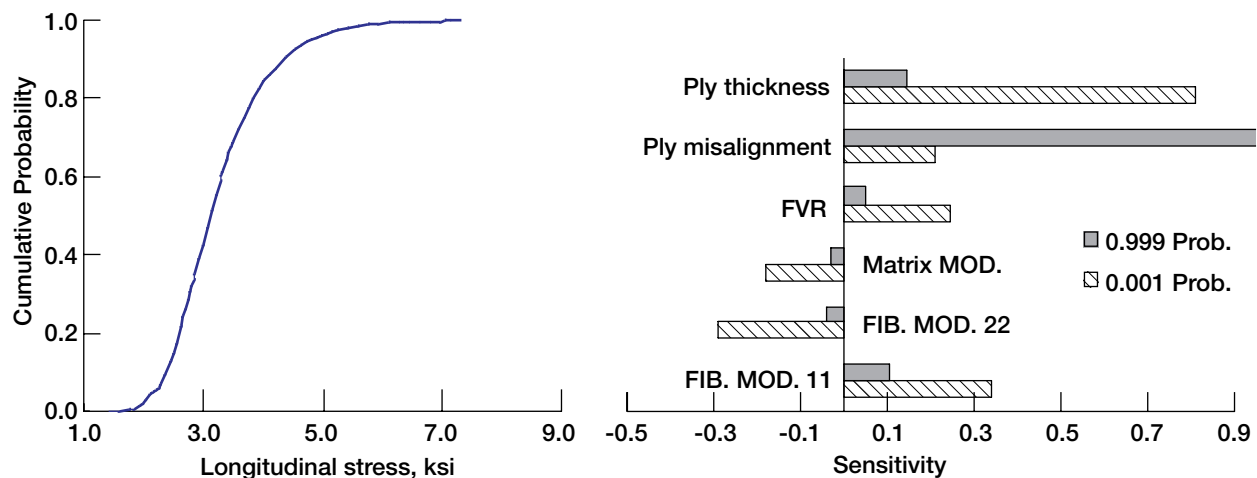
Figure 8.—(a) Cumulative distribution function of the longitudinal stress at root in a 90 degree ply. (b) Sensitivity of longitudinal stress in a 90 degree ply at root to the primitive variables.
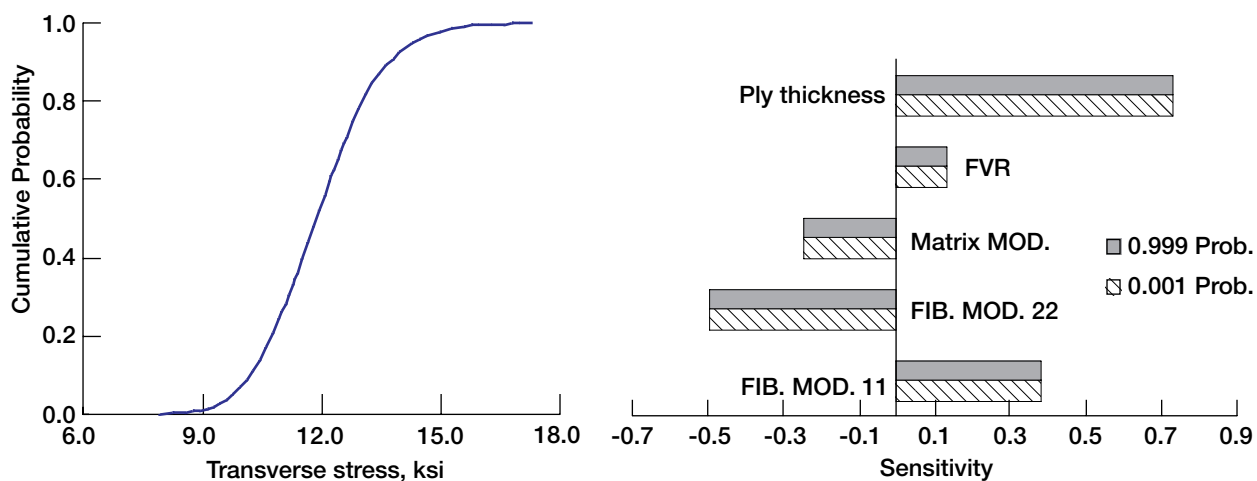


Figure 9.—(a) Cumulative distribution function of the transverse stress at root in a 90 degree ply. (b) Sensitivity of transverse stress in a 90 degree ply at root to the primitive variables.
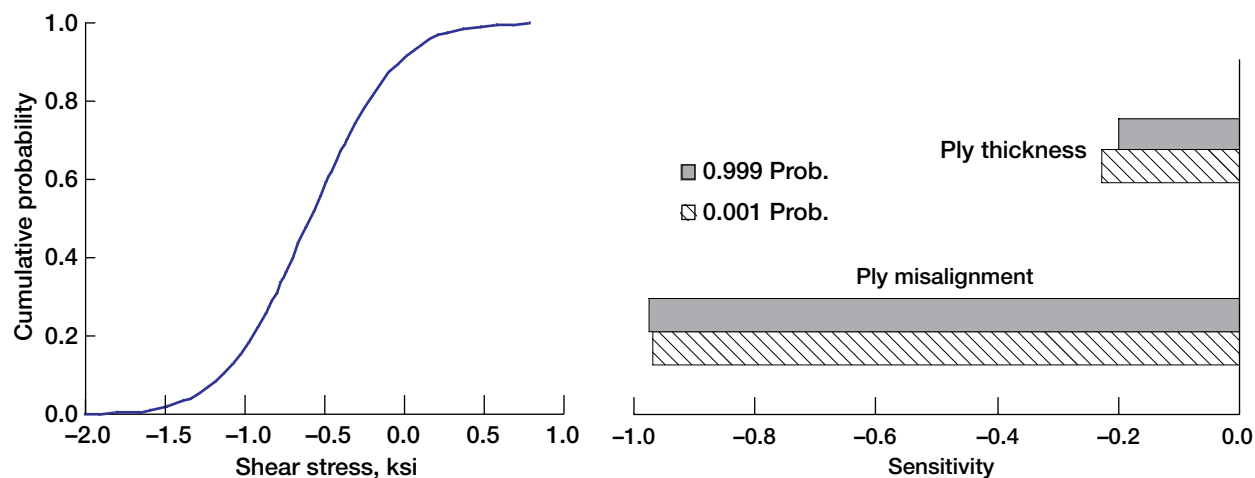
Figure 10.—(a) Cumulative distribution function of the shear stress at root in a 90 degree ply. (b) Sensitivity of shear stress in a 90 degree ply at root to the primitive variables.
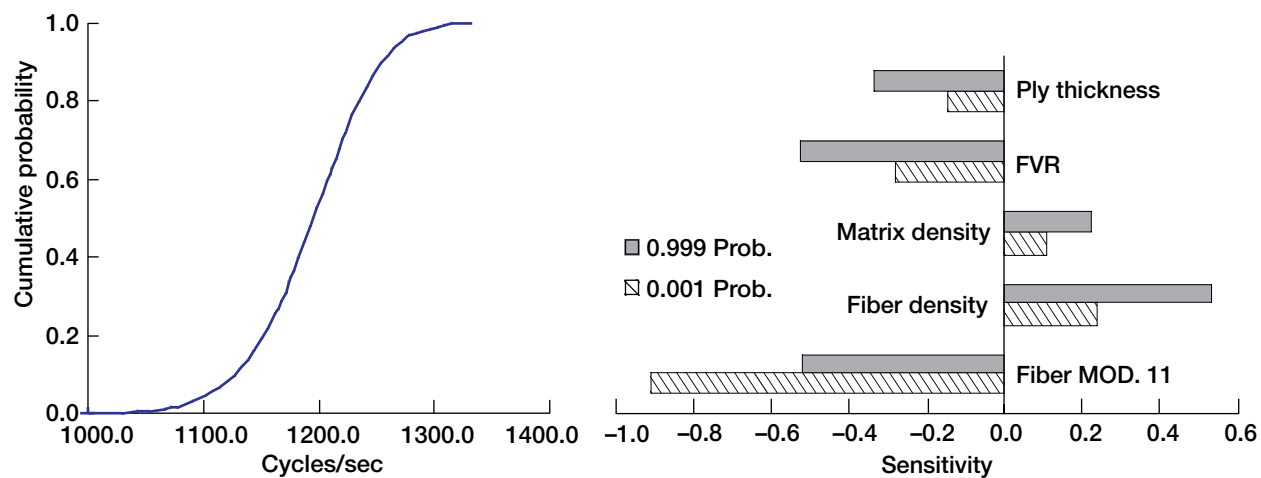


Figure 11.—(a) Cumulative distribution function of the first natural frequency. (b) Sensitivity of the first natural frequency to the primitive variables.
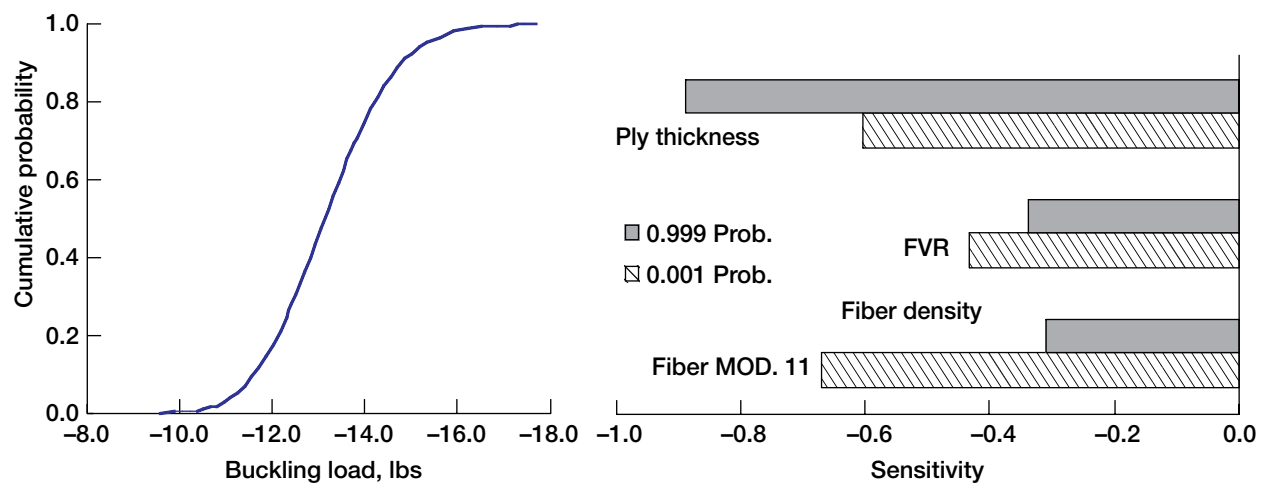
Figure 12.—(a) Cumulative distribution function of the critical buckling load. (b) Sensitivity of the critical buckling to the primitive variables.

# APPENDIX E:     ALCCA SAMPLE OUTPUT

```
        **************************************************
        **                   ALCCA                    **
        **      Aircraft Life Cycle Cost Analysis     **
        **      IBM RS/6000  FLOPS Module Version      **
        **                                            **
        **      Aerospace Systems Design Laboratory    **
        **        Georgia Tech, Atlanta GA 30332       **
        **************************************************

 ============ UNIT PRODUCTION COSTS == 1992. DOLLARS ============

 Breakdown of Manufacturing Cost    Inflated from 1970 base dollars at  8.00% rate
  AMPR Weight/Takeoff Gross Weight (lbs)      200132./ 735187.
  Monthly Production Rate   (ac/mon)      7.00

  Group                         CF      EF     % W        Weight            Cost
   STRUCTURE                                           149735.000         195.336
    WING                                                55012.766          89.187
        Aluminum              1.00    1.00     0.           0.0            0.000
        Titanium              1.51    1.00    70.       38508.9           42.088
        Composite             0.50    1.23    30.       16503.8           47.100
    EMPENNAGE                                            5936.420           9.283
        Aluminum              1.00    1.00     0.           0.0            0.000
        Titanium              1.51    1.00    85.        5046.0            7.207
        Composite             0.50    1.23    15.         890.5            2.076
    FUSELAGE                                            59940.355          76.697
        Aluminum              1.00    1.00     0.           0.0            0.000
        Titanium              1.42    1.00   100.       59940.4           76.697
        Composite             0.35    1.31     0.           0.0            0.000
    LANDING GEAR                                        28845.453          20.169
        Aluminum              1.00    1.00    50.       14422.7           10.084
        Titanium              1.00    1.00    50.       14422.7           10.084
        Composite             1.00    1.00     0.           0.0            0.000
    NACELLES/PYLONS                                         0.000           0.000
        Aluminum              1.00    1.00     0.           0.0            0.000
        Titanium              1.00    1.00   100.           0.0            0.000
        Composite             1.00    1.00     0.           0.0            0.000

   ENGINES                       3.00                   66788.000          77.256

   AIRFRAME PROPULSION                                   4938.445           1.662
    THRUST REVERSER           1.00    1.00                  0.000           0.000
    FUEL SYSTEM               1.00    1.00               4938.445           1.662
    ENGINE ACCESSORIES        1.00    1.00                  0.000           0.000

   FIXED EQUIPMENT                                       59659.789          60.749
    AERODYNAMIC CONTROLS      1.00    1.00              10778.502          23.439
    HYDRAULIC                 1.00    1.00               4787.303           7.059
    ELECTRICAL POWER          1.00    1.00               5518.508           7.871
    AIR CONDITIONING          1.00    1.00               8682.571           3.455
    ANTI-ICING                1.00    1.00                377.509           0.472
    AUXILIARY POWER SOURCE    1.00    1.00                  0.000           0.000
    PASSENGER ACCOMMODATIONS  1.00    1.00              29515.398          18.453

   INSTRUMENTATION            1.00    1.00               2004.900          11.358
    EQUIPMENT                                                              10.518
    INSTALLATION                                                            0.839

   AVIONICS                   1.00    1.00               3058.248          17.325
    EQUIPMENT                                                              16.044
    INSTALLATION                                                            1.280

   LOAD AND HANDLING          1.00    1.00                                  0.000
   FINAL ASSEMBLY AND CHECKOUT                                            18.380

   VEHICLE TOTAL                                        286184.375         382.065


 Manufacturing - First Unit Cost (FUC)        (  382.065) Spares not included
        Airframe                              (  257.747)
        Avionics & Instrumentation            (   28.682)
```

```
      Propulsion                                    (  77.256)
      Assembly                                      (  18.380)


    ============ PRODUCTION AND RDT&E COSTS == 1992. DOLLARS ============


      ***** Millions of U.S. dollars *****
    RESEARCH,DEVELOPMENT,TEST,AND EVALUATION                              22399.066
      AIRFRAME DEVELOPMENT      (Eng. labor $65./hr)      5932.594
        CONCEPT FORMULATION    (    150. man-yrs)       15.210
        CONTRACT DEFINITION    (    500. man-yrs)       67.600
        AIRFRAME ENGINEERING   (  43268. man-yrs)     5849.784
      SUBSYSTEMS DEVELOPMENT                             1396.944
      AVIONICS DEVELOPMENT      (1.00x Factor)           1142.428
      PROPULSION DEVELOPMENT    ( 53.% Spares)           5098.428
      DEVELOPMENT SUPPORT                                4066.667
        GROUND TEST VEHICLES   (1. aircraft)            257.747
        GROUND TEST SPARES     (10.0% of GTV)            25.775
        FLIGHT TEST SPARES     (20.0% of FTV)            76.413
        TOOLING EQUIPMENT      (Tooling labor $55./hr) 3162.146
        FLIGHT TEST OPERATIONS (1. aircraft)           183.005
        GROUND SUPPORT EQUIPMENT                        353.940
        TECHNICAL DATA                                    7.641
      FEE                      (27.0% profit)            4762.006


    AIRCRAFT PRODUCTION                                                  165535.984
      OPERATIONAL VEHICLES     ( 504. aircraft)        80723.586
      SPARES - Airframe        ( 6.0% of Afrm)          7388.542
            - Engines          (23.0% of Engs)          8955.563
      FACILITIES                                            0.000
      SUSTAINING ENGINEERING                            14660.934
      SUSTAINING TOOLING                                 4394.380
      GROUND SUPPORT EQUIPMENT                          12108.538
      TECHNICAL DATA           ( 2% of OV)               1614.472
      MISCELLANEOUS EQUIPMENT                              32.945
      TRAINING EQUIPMENT                                    0.000
      INITIAL TRAINING                                     0.000
      INITIAL TRANSPORTATION                             464.325
      FEE                      (27.0% profit)           35192.691

    TOTAL COST               ( 504. aircraft)                           187935.047
    AVERAGE UNIT AIRPLANE COST  (including spares)                          372.887
    AVERAGE UNIT AIRPLANE COST  (excluding spares)                          331.702


    ============ PRODUCTION COST VS. QUANTITY == 1992. DOLLARS ============

    Aircraft Cost Versus Quantity


    Learning Curve Percentages
               FIRST LOT   SECOND LOT
     Airframe       86.5        86.5
     Avionics       86.5        86.5
     Propulsion    100.0       100.0
     Fixed Eqpm.    86.5        86.5
     Integ. & Assembly 86.5     86.5
     Production Line Learning Curve Breaking Point    200.
     Propulsion based on production of 2500. engines

        ***** Average Manufacturing Costs *****         RDT&E  Sustaining Average
     Number Airframe Propulsion Avionics Unit      Cum.    Costs   Costs      Cost

        1 257.747   77.256   28.682 485.223    485.223  16071.595  1146.7317703.551
        2 222.951   77.256   24.810 432.964    865.927  16303.068  2535.31 9852.153
        3 204.817   77.256   22.792 405.728   1217.185  16479.281  3485.78 7060.750
        4 192.853   77.256   21.461 387.759   1551.036  16623.479  4237.33 5602.961
        5 184.056   77.256   20.482 374.547   1872.736  16746.535  4871.97 4698.249
        6 177.167   77.256   19.715 364.201   2185.205  16854.475  5428.56 4078.039
        7 171.544   77.256   19.089 355.756   2490.290  16951.008  5928.82 3624.302
        8 166.818   77.256   18.563 348.657   2789.258  17038.600  6386.25 3276.764
        9 162.757   77.256   18.112 342.559   3083.026  17118.967  6809.88 3001.319
       10 159.208   77.256   17.717 337.229   3372.288  17193.365  7206.03 2777.168
       20 137.715   77.256   15.325 304.949   6098.972  17744.881 10307.89 1707.587
```

| 30 | 126.514 | 77.256 | 14.079 | 288.126 | 8643.771 | 18121.723 | 12647.44 | 1313.764 |
|---|---|---|---|---|---|---|---|---|
| 40 | 119.124 | 77.256 | 13.256 | 277.026 | 11081.045 | 18416.236 | 14630.96 | 1103.206 |
| 50 | 113.690 | 77.256 | 12.651 | 268.865 | 13443.259 | 18661.566 | 16400.89 | 970.114 |
| 60 | 109.435 | 77.256 | 12.178 | 262.474 | 15748.459 | 18873.750 | 18025.81 | 877.467 |
| 70 | 105.961 | 77.256 | 11.791 | 257.258 | 18008.051 | 19061.869 | 19544.60 | 808.779 |
| 80 | 103.042 | 77.256 | 11.467 | 252.873 | 20229.859 | 19231.615 | 20981.66 | 755.539 |
| 90 | 100.534 | 77.256 | 11.187 | 249.106 | 22419.547 | 19386.811 | 22353.48 | 712.887 |
| 100 | 98.342 | 77.256 | 10.943 | 245.814 | 24581.400 | 19530.154 | 23671.72 | 677.833 |
| 200 | 85.066 | 77.256 | 9.466 | 225.875 | 45174.941 | 20591.379 | 35130.90 | 504.486 |
| 300 | 78.147 | 77.256 | 8.696 | 215.483 | 64645.000 | 21321.711 | 44998.68 | 436.551 |
| 400 | 73.582 | 77.256 | 8.188 | 208.627 | 83450.906 | 21897.609 | 54083.55 | 398.580 |
| 500 | 70.225 | 77.256 | 7.815 | 203.586 | 101793.148 | 22381.166 | 62680.83 | 373.710 |
| 600 | 67.597 | 77.256 | 7.522 | 199.639 | 119783.211 | 22802.270 | 70937.05 | 355.871 |
| 700 | 65.452 | 77.256 | 7.283 | 196.417 | 137491.594 | 23177.857 | 78937.31 | 342.295 |
| 800 | 63.648 | 77.256 | 7.083 | 193.708 | 154966.547 | 23518.555 | 86736.18 | 331.527 |
| 900 | 62.099 | 77.256 | 6.910 | 191.381 | 172243.109 | 23831.504 | 94371.16 | 322.717 |
| 1000 | 60.745 | 77.256 | 6.760 | 189.348 | 189347.750 | 24121.773 | 101869.24 | 315.339 |

```
============ MANUFACTURERS CUMULATIVE CASHFLOW == 1992. DOLLARS ============
Production Size       =       504.
Average Aircraft Price =      $  298.3 M
```

| Year | Annual Deliveries | Cumulative Deliveries | Costs RDT&E | Manufacturing | Sustaining | Income | Net Cashflow |
|---|---|---|---|---|---|---|---|
| 2000 | 0.0 | 0.0 | 1019.7 | 0.0 | 0.0 | 348.3 | -671.4 |
| 2001 | 0.0 | 0.0 | 4157.4 | 0.0 | 0.0 | 1336.0 | -2821.3 |
| 2002 | 0.0 | 0.0 | 8311.7 | 0.0 | 0.0 | 3080.4 | -5231.3 |
| 2003 | 0.0 | 0.0 | 12466.1 | 0.0 | 0.0 | 5636.8 | -6829.2 |
| 2004 | 0.0 | 0.0 | 16620.4 | 2790.3 | 8258.2 | 9084.3 | -18584.6 |
| 2005 | 24.0 | 24.0 | 17637.1 | 9798.5 | 17734.6 | 18760.5 | -26409.7 |
| 2006 | 48.0 | 72.0 | 17637.1 | 19241.6 | 24514.6 | 34458.2 | -26935.1 |
| 2007 | 60.0 | 132.0 | 17637.1 | 29527.6 | 29972.1 | 53287.5 | -23849.2 |
| 2008 | 66.0 | 198.0 | 17637.1 | 40379.1 | 34816.0 | 72530.9 | -20301.2 |
| 2009 | 72.0 | 270.0 | 17637.1 | 51341.5 | 39198.1 | 92309.2 | -15867.5 |
| 2010 | 72.0 | 342.0 | 17637.1 | 62403.9 | 43291.8 | 111213.7 | -12119.0 |
| 2011 | 78.0 | 420.0 | 17637.1 | 74187.2 | 47409.3 | 130586.4 | -8647.2 |
| 2012 | 84.0 | 504.0 | 17637.1 | 80723.6 | 49619.7 | 150348.2 | 2367.9 |
| Totals | | 504.0 | 17637.1 | 80723.6 | 49619.7 | 150348.2 | 2367.9 |

```
============ MANUFACTURERS ANNUAL CASHFLOW == 1992. DOLLARS ============
Production Size       =       504.
Average Aircraft Price =      $  298.3 M
```

| Year | Annual Deliveries | Cumulative Deliveries | Costs RDT&E | Manufacturing | Sustaining | Income | Annual Cashflow |
|---|---|---|---|---|---|---|---|
| 2000 | 0.0 | 0.0 | 1019.7 | 0.0 | 0.0 | 348.3 | -671.4 |
| 2001 | 0.0 | 0.0 | 3137.7 | 0.0 | 0.0 | 987.8 | -2149.9 |
| 2002 | 0.0 | 0.0 | 4154.3 | 0.0 | 0.0 | 1744.4 | -2410.0 |
| 2003 | 0.0 | 0.0 | 4154.3 | 0.0 | 0.0 | 2556.5 | -1597.9 |
| 2004 | 0.0 | 0.0 | 4154.3 | 2790.3 | 8258.2 | 3447.4 | -11755.4 |
| 2005 | 24.0 | 24.0 | 1016.7 | 7008.2 | 9476.1 | 9676.2 | -7825.1 |
| 2006 | 48.0 | 72.0 | 0.0 | 9443.1 | 6780.0 | 15697.7 | -525.4 |
| 2007 | 60.0 | 132.0 | 0.0 | 10286.0 | 5457.5 | 18829.3 | 3085.9 |
| 2008 | 66.0 | 198.0 | 0.0 | 10851.5 | 4843.9 | 19243.4 | 3547.9 |
| 2009 | 72.0 | 270.0 | 0.0 | 10962.5 | 4382.1 | 19778.3 | 4433.7 |
| 2010 | 72.0 | 342.0 | 0.0 | 11062.5 | 4093.7 | 18904.6 | 3748.6 |
| 2011 | 78.0 | 420.0 | 0.0 | 11783.3 | 4117.6 | 19372.6 | 3471.8 |
| 2012 | 84.0 | 504.0 | 0.0 | 6536.4 | 2210.4 | 19761.9 | 11015.1 |
| Totals | | 504.0 | 17637.1 | 80723.6 | 49619.7 | 150348.2 | 2367.9 |

```
============ MANUFACTURERS CUMULATIVE CASHFLOW == 1992. DOLLARS ============
Production Size       =       504.
Average Aircraft Price =      $  335.6 M
```

| Year | Annual Deliveries | Cumulative Deliveries | Costs RDT&E | Manufacturing | Sustaining | Income | Net Cashflow |
|---|---|---|---|---|---|---|---|
| 2000 | 0.0 | 0.0 | 1019.7 | 0.0 | 0.0 | 391.8 | -627.9 |
| 2001 | 0.0 | 0.0 | 4157.4 | 0.0 | 0.0 | 1503.0 | -2654.3 |
| 2002 | 0.0 | 0.0 | 8311.7 | 0.0 | 0.0 | 3465.4 | -4846.3 |
| 2003 | 0.0 | 0.0 | 12466.1 | 0.0 | 0.0 | 6341.4 | -6124.6 |
| 2004 | 0.0 | 0.0 | 16620.4 | 2790.3 | 8258.2 | 10219.8 | -17449.1 |

```
2005    24.0      24.0    17637.1     9798.5    17734.6  21105.5 -24064.6
2006    48.0      72.0    17637.1    19241.6    24514.6  38765.2 -22628.1
2007    60.0     132.0    17637.1    29527.6    29972.1  59947.9 -17188.7
2008    66.0     198.0    17637.1    40379.1    34816.0  81596.6 -11235.6
2009    72.0     270.0    17637.1    51341.5    39198.1 103846.9  -4329.8
2010    72.0     342.0    17637.1    62403.9    43291.8 125114.4   1781.7
2011    78.0     420.0    17637.1    74187.2    47409.3 146908.5   7675.0
2012    84.0     504.0    17637.1    80723.6    49619.7 169140.6  21160.3
Totals           504.0    17637.1    80723.6    49619.7 169140.6  21160.3


============ MANUFACTURERS ANNUAL CASHFLOW == 1992. DOLLARS ============
Production Size      =       504.
Average Aircraft Price  =     $  335.6 M

Year   Annual   Cumulative          Costs                    Income   Annual
       Deliveries  Deliveries RDT&E Manufacturing Sustaining          Cashflow

2000    0.0       0.0    1019.7       0.0        0.0    391.8    -627.9
2001    0.0       0.0    3137.7       0.0        0.0   1111.2   -2026.4
2002    0.0       0.0    4154.3       0.0        0.0   1962.4   -2191.9
2003    0.0       0.0    4154.3       0.0        0.0   2876.0   -1278.3
2004    0.0       0.0    4154.3    2790.3     8258.2   3878.4  -11324.5
2005   24.0      24.0    1016.7    7008.2     9476.4  10885.7   -6615.5
2006   48.0      72.0       0.0    9443.1     6780.0  17659.7    1436.5
2007   60.0     132.0       0.0   10286.0     5457.5  21182.8    5439.3
2008   66.0     198.0       0.0   10851.5     4843.9  21648.6    5953.1
2009   72.0     270.0       0.0   10962.5     4382.1  22250.3    6905.8
2010   72.0     342.0       0.0   11062.3     4093.7  21267.5    6111.5
2011   78.0     420.0       0.0   11783.3     4117.6  21794.1    5893.3
2012   84.0     504.0       0.0    6536.4     2210.4  22232.0   13485.3
Totals          504.0   17637.1   80723.6    49619.7 169140.6   21160.3


============ MANUFACTURERS CUMULATIVE CASHFLOW == 1992. DOLLARS ============
Production Size      =       504.
Average Aircraft Price  =     $  410.2 M

Year   Annual   Cumulative          Costs                    Income   Net
       Deliveries  Deliveries RDT&E Manufacturing Sustaining          Cashflow

2000    0.0       0.0    1019.7       0.0        0.0    478.9    -540.8
2001    0.0       0.0    4157.4       0.0        0.0   1837.0   -2320.3
2002    0.0       0.0    8311.7       0.0        0.0   4235.5   -4076.2
2003    0.0       0.0   12466.1       0.0        0.0   7750.7   -4715.4
2004    0.0       0.0   16620.4    2790.3     8258.2  12490.9  -15178.0
2005   24.0      24.0   17637.1    9798.5    17734.6  25795.6  -19374.5
2006   48.0      72.0   17637.1   19241.6    24514.6  47379.7  -14013.5
2007   60.0     132.0   17637.1   29527.6    29972.1  73269.8   -3866.9
2008   66.0     198.0   17637.1   40379.1    34816.0  99729.3    6897.1
2009   72.0     270.0   17637.1   51341.5    39198.1 126924.2   18747.5
2010   72.0     342.0   17637.1   62403.9    43291.8 152917.8   29585.1
2011   78.0     420.0   17637.1   74187.2    47409.3 179555.1   40321.5
2012   84.0     504.0   17637.1   80723.6    49619.7 206727.6   58747.3
Totals          504.0   17637.1   80723.6    49619.7 206727.6   58747.3


============ MANUFACTURERS ANNUAL CASHFLOW == 1992. DOLLARS ============
Production Size      =       504.
Average Aircraft Price  =     $  410.2 M

Year   Annual   Cumulative          Costs                    Income   Annual
       Deliveries  Deliveries RDT&E Manufacturing Sustaining          Cashflow

2000    0.0       0.0    1019.7       0.0        0.0    478.9    -540.8
2001    0.0       0.0    3137.7       0.0        0.0   1358.2   -1779.5
2002    0.0       0.0    4154.3       0.0        0.0   2398.5   -1755.9
2003    0.0       0.0    4154.3       0.0        0.0   3515.1    -639.2
2004    0.0       0.0    4154.3    2790.3     8258.2   4740.2  -10462.6
2005   24.0      24.0    1016.7    7008.2     9476.4  13304.8   -4196.5
2006   48.0      72.0       0.0    9443.1     6780.0  21584.1    5361.0
2007   60.0     132.0       0.0   10286.0     5457.5  25890.1   10146.7
2008   66.0     198.0       0.0   10851.5     4843.9  26459.5   10764.0
2009   72.0     270.0       0.0   10962.5     4382.1  27194.9   11850.4
2010   72.0     342.0       0.0   11062.3     4093.7  25993.6   10837.6
2011   78.0     420.0       0.0   11783.3     4117.6  26637.3   10736.4
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2012   84.0     504.0       0.0    6536.4   2210.4 27172.5 18425.7
Totals           504.0   17637.1   80723.6  49619.7 206727.6 58747.3


============ MANUFACTURERS CUMULATIVE CASHFLOW == 1992. DOLLARS ============
Production Size        =       504.
Average Aircraft Price =    $  447.5 M

Year   Annual   Cumulative                  Costs            Income   Net
       Deliveries Deliveries RDT&E Manufacturing Sustaining        Cashflow

2000   0.0      0.0    1019.7      0.0      0.0     522.4   -497.3
2001   0.0      0.0    4157.4      0.0      0.0    2004.0  -2153.3
2002   0.0      0.0    8311.7      0.0      0.0    4620.6  -3691.1
2003   0.0      0.0   12466.1      0.0      0.0    8455.3  -4010.8
2004   0.0      0.0   16620.4   2790.3   8258.2   13626.4 -14042.5
2005  24.0     24.0   17637.1   9798.5  17734.6   28140.7 -17029.4
2006  48.0     72.0   17637.1  19241.6  24514.6   51687.3  -9706.0
2007  60.0    132.0   17637.1  29527.6  29972.1   79931.3   2794.6
2008  66.0    198.0   17637.1  40379.1  34816.0  108796.4  15964.2
2009  72.0    270.0   17637.1  51341.5  39198.1  138463.8  30287.1
2010  72.0    342.0   17637.1  62403.9  43291.8  166820.6  43487.9
2011  78.0    420.0   17637.1  74187.2  47409.3  195879.6  56646.0
2012  84.0    504.0   17637.1  80723.6  49619.7  225522.3  77542.0
Totals         504.0   17637.1  80723.6  49619.7  225522.3  77542.0


============ MANUFACTURERS ANNUAL CASHFLOW == 1992. DOLLARS ============
Production Size        =       504.
Average Aircraft Price =    $  447.5 M

Year   Annual   Cumulative                  Costs            Income   Annual
       Deliveries Deliveries RDT&E Manufacturing Sustaining        Cashflow

2000   0.0      0.0    1019.7      0.0      0.0     522.4   -497.3
2001   0.0      0.0    3137.7      0.0      0.0    1481.6  -1656.0
2002   0.0      0.0    4154.3      0.0      0.0    2616.5  -1537.8
2003   0.0      0.0    4154.3      0.0      0.0    3834.7   -319.6
2004   0.0      0.0    4154.3   2790.3   8258.2    5171.2 -10031.7
2005  24.0     24.0    1016.7   7008.2   9476.4   14514.3  -2987.0
2006  48.0     72.0       0.0   9443.1   6780.0   23546.5   7323.4
2007  60.0    132.0       0.0  10286.0   5457.5   28244.0  12500.6
2008  66.0    198.0       0.0  10851.5   4843.9   28865.1  13169.7
2009  72.0    270.0       0.0  10962.5   4382.1   29667.4  14322.8
2010  72.0    342.0       0.0  11062.3   4093.7   28356.8  13200.8
2011  78.0    420.0       0.0  11783.3   4117.6   29058.9  13158.1
2012  84.0    504.0       0.0   6536.4   2210.4   29642.8  20896.0
Totals         504.0   17637.1  80723.6  49619.7  225522.3  77542.0


============ MANUFACTURERS CUMULATIVE CASHFLOW == 1992. DOLLARS ============
Production Size        =       504.
Average Aircraft Price =    $  484.8 M

Year   Annual   Cumulative                  Costs            Income   Net
       Deliveries Deliveries RDT&E Manufacturing Sustaining        Cashflow

2000   0.0      0.0    1019.7      0.0      0.0     565.9   -453.8
2001   0.0      0.0    4157.4      0.0      0.0    2171.0  -1986.3
2002   0.0      0.0    8311.7      0.0      0.0    5005.6  -3306.1
2003   0.0      0.0   12466.1      0.0      0.0    9159.9  -3306.2
2004   0.0      0.0   16620.4   2790.3   8258.2   14761.9 -12906.9
2005  24.0     24.0   17637.1   9798.5  17734.6   30485.7 -14684.5
2006  48.0     72.0   17637.1  19241.6  24514.6   55994.2  -5399.1
2007  60.0    132.0   17637.1  29527.6  29972.1   86591.9   9455.3
2008  66.0    198.0   17637.1  40379.1  34816.0  117862.7  25030.5
2009  72.0    270.0   17637.1  51341.5  39198.1  150002.5  41825.8
2010  72.0    342.0   17637.1  62403.9  43291.8  180722.6  57389.9
2011  78.0    420.0   17637.1  74187.2  47409.3  212203.3  72969.7
2012  84.0    504.0   17637.1  80723.6  49619.7  244316.3  96336.0
Totals         504.0   17637.1  80723.6  49619.7  244316.3  96336.0
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============ MANUFACTURERS ANNUAL CASHFLOW == 1992. DOLLARS ============
Production Size        =      504.
Average Aircraft Price =    $  484.8 M

Year    Annual   Cumulative         Costs                    Income   Annual
       Deliveries Deliveries RDT&E Manufacturing Sustaining          Cashflow

2000     0.0      0.0     1019.7       0.0         0.0      565.9    -453.8
2001     0.0      0.0     3137.7       0.0         0.0     1605.1   -1532.6
2002     0.0      0.0     4154.3       0.0         0.0     2834.6   -1319.8
2003     0.0      0.0     4154.3       0.0         0.0     4154.2      -0.1
2004     0.0      0.0     4154.3    2790.3      8258.2     5602.1   -9600.7
2005    24.0     24.0     1016.7    7008.2      9476.4    15723.7   -1777.5
2006    48.0     72.0        0.0    9443.1      6780.0    25508.5    9285.4
2007    60.0    132.0        0.0   10286.0      5457.5    30597.8   14854.3
2008    66.0    198.0        0.0   10851.5      4843.9    31270.8   15575.3
2009    72.0    270.0        0.0   10962.5      4382.1    32139.9   16795.3
2010    72.0    342.0        0.0   11062.3      4093.7    30720.1   15564.1
2011    78.0    420.0        0.0   11783.3      4117.6    31480.6   15579.8
2012    84.0    504.0        0.0    6536.4      2210.4    32113.0   23366.3
Totals          504.0    17637.1   80723.6     49619.7 244316.3   96336.0


============ MANUFACTURERS CUMULATIVE CASHFLOW == 1992. DOLLARS ============
Production Size        =      504.
Average Aircraft Price =    $  372.9 M

Year    Annual   Cumulative                   Costs         Income   Net
       Deliveries Deliveries RDT&E Manufacturing Sustaining          Cashflow

2000     0.0      0.0     1019.7       0.0         0.0      435.3    -584.4
2001     0.0      0.0     4157.4       0.0         0.0     1670.0   -2487.3
2002     0.0      0.0     8311.7       0.0         0.0     3850.5   -4461.2
2003     0.0      0.0    12466.1       0.0         0.0     7046.0   -5420.0
2004     0.0      0.0    16620.4    2790.3      8258.2    11355.4  -16313.5
2005    24.0     24.0    17637.1    9798.5     17734.6    23450.6  -21719.5
2006    48.0     72.0    17637.1   19241.6     24514.6    43072.7  -18320.5
2007    60.0    132.0    17637.1   29527.6     29972.1    66609.4  -10527.3
2008    66.0    198.0    17637.1   40379.1     34816.0    90663.6   -2168.5
2009    72.0    270.0    17637.1   51341.5     39198.1   115386.4    7209.7
2010    72.0    342.0    17637.1   62403.9     43291.8   139017.1   15684.4
2011    78.0    420.0    17637.1   74187.2     47409.3   163232.9   23999.3
2012    84.0    504.0    17637.1   80723.6     49619.7   187935.1   39954.8
Totals          504.0    17637.1   80723.6     49619.7 187935.1   39954.8


============ MANUFACTURERS ANNUAL CASHFLOW == 1992. DOLLARS ============
Production Size        =      504.
Average Aircraft Price =    $  372.9 M

Year    Annual   Cumulative         Costs                    Income   Annual
       Deliveries Deliveries RDT&E Manufacturing Sustaining          Cashflow

2000     0.0      0.0     1019.7       0.0         0.0      435.3    -584.4
2001     0.0      0.0     3137.7       0.0         0.0     1234.7   -1903.0
2002     0.0      0.0     4154.3       0.0         0.0     2180.4   -1973.9
2003     0.0      0.0     4154.3       0.0         0.0     3195.6    -958.8
2004     0.0      0.0     4154.3    2790.3      8258.2     4309.3  -10893.5
2005    24.0     24.0     1016.7    7008.2      9476.4    12095.2   -5406.0
2006    48.0     72.0        0.0    9443.1      6780.0    19622.1    3399.0
2007    60.0    132.0        0.0   10286.0      5457.5    23536.7    7793.3
2008    66.0    198.0        0.0   10851.5      4843.9    24054.2    8358.8
2009    72.0    270.0        0.0   10962.5      4382.1    24722.8    9378.3
2010    72.0    342.0        0.0   11062.3      4093.7    23630.7    8474.7
2011    78.0    420.0        0.0   11783.3      4117.6    24215.7    8314.9
2012    84.0    504.0        0.0    6536.4      2210.4    24702.3   15955.5
Totals          504.0    17637.1   80723.6     49619.7 187935.1   39954.8
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============ MANUFACTURERS RETURN ON INVESTMENT == 1992. DOLLARS ============


Production Size =  400.
Monthly Rate =  1.6 3.2 4.0 4.4 4.8 4.8 5.2 5.6 0.0 0.0 0.0 0.0 0.0 0.0 0.0

Aircraft Price (Mill. $)  ROI Manufacturing (%)   Profit (Mill. $)   Breakeven Unit #
          411.404                 1.40                2590.609            390.
          462.829                12.40               23162.453            234.
          514.254                22.20               43732.078            154.
          565.680                31.60               64301.672            110.
          617.105                40.90               84871.500             82.
          668.531                50.40              105441.375             62.


Production Size =  800.
Monthly Rate =  3.2 6.3 7.9 8.7 9.5 9.510.311.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0

Aircraft Price (Mill. $)  ROI Manufacturing (%)   Profit (Mill. $)   Breakeven Unit #
          292.467                 1.70                3685.859            779.
          329.026                14.50               32928.750            449.
          365.584                26.70               62177.719            280.
          402.142                39.20               91427.188            195.
          438.701                53.30              120669.375            147.
          475.259                70.50              149918.937            109.


Production Size =  504.
Monthly Rate =  2.0 4.0 5.0 5.5 6.0 6.0 6.5 7.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

Aircraft Price (Mill. $)  ROI Manufacturing (%)   Profit (Mill. $)   Breakeven Unit #
          298.309                 1.30                2367.922            491.
          335.598                10.90               21160.250            319.
          372.887                19.60               39954.828            211.
          410.175                27.80               58747.281            155.
          447.464                35.80               77542.000            118.
          484.753                43.80               96335.984             93.


Return on Investment =  12. %
Aircraft Price       = 340.313



============ DOC, IOC, & TOC ==  504. UNITS == 1992. DOLLARS ============

  Airframe Cost          (millions $)             232.218
  Engine Cost            (per engine)              17.627
  Spares Cost            (airframe and engine)     41.185
  Number of First Class/Coach Passengers           0./292.
  Annual Utiliz., Sup. Cruise Mach # and Alt.   4000.0 hrs   at M = 2.40 and  57840. ft
  Subsonic Cruise Mach # and Alt.              M = 0.90 and   35000. ft
  Trips per year                                668.    1102.    756.   1161.
  Stage Length           (sm)                  6621.    3682.   5754.   3452.
  Stage Length           (nmi)                 5754.    3200.   5000.   3000.
  Block Speed            (mph)                  1105.    1015.   1087.   1002.
       Time              (hr)                   5.991   3.630   5.294   3.445
  Ground Time Idle/Maneuver (hr)               1.500/0.180
  Flight Time            (hr)                   5.811   3.450   5.114   3.265
  Climb + Descent Time   (hr)                  0.857
  Cruise Time            (hr)                   5.134   2.773   4.437   2.588
  Block Fuel             (lb)              379098. 213591. 330295. 200595.
  Block Fuel             (gal/hr)               9374.   8718.   9243.   8627.

Direct Operating Costs $/Trip

  Flying Operations Costs:  3. person crew
    Flight Crew      ($ 828./Blk hr)            4961.   3397.   4499.   3274.
    Fuel and Oil     ($0.65/gal)               37242.  20983.  32448.  19707.
    Total                                      42203.  24380.  36947.  22981.

Direct Maintenance Costs:  Labor rate $ 19.50/hr *** Engine Removal Rate (/1000 EFH) 0.100
    Airframe Labor   (1.00 Complexity)          1620.   1110.   1469.   1070.
                     (Man hr/Flight hr)         14.3    16.5    14.7    16.8
           Burden  (200.% of Labor)             3240.   2220.   2939.   2141.
           Material                             2803.   1958.   2553.   1892.
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      Engine Labor Total (1.00 Complexity)        156.       93.      138.       88.
         Line Maint. Labor Cost                     37.       22.       33.       21.
              (Man hrs per Installation)            71.9      71.9      71.9      71.9
         Shop Maint. Labor Cost                     56.       33.       49.       31.
         Basic Eng. Maint. Labor Cost               82.       49.       73.       46.
              (Man hrs for QEC build-up)           791.4     791.4     791.4     791.4
         Outside Service Labor (   0. % Labor)       0.        0.        0.        0.
            Burden    (200.% of Labor)             313.      186.      275.      176.
      Engine Material Cost                         4577.     2717.     4028.     2571.
         Line Maint. Material Cost                   75.       44.       66.       42.
         Shop Maint. Material Cost                  135.       80.      119.       76.
         Basic Eng. Maint. Material Cost           4368.     2593.     3844.     2454.
         Outside Service Material Cost               0.        0.        0.        0.
      Total                                       12709.     8284.    11402.     7938.

   Investment Costs:  averaged
      Depreciation      (20. years,10.% residual)  22937.    13896.    20268.    13188.
      Financing         (100.% @  8.00% interest)  26430.    16012.    23354.    15196.
      Hull Insurance    (.35% aircraft cost)        1784.     1081.     1576.     1026.
      Total                                        51151.    30988.    45198.    29409.

   Total Direct Operating Cost
      $/Trip-DOC                                  106062.    63652.    93548.    60328.
      $/Flight hr                                  18252.    18453.    18293.    18480.
      $/Block hr                                   17703.    17537.    17671.    17514.
      $/Aircraft Mile                                16.02     17.29     16.26     17.47
      $/ASM                                       .054856   .059197   .055679   .059845

   DOC per Aircraft Trip Equation = $   10515.77 + $  14.43/sm
   DOC per available seat trip = $       36.01 + $ 0.0494/sm


   OliverDOC = .059197
 Indirect Operating Costs $/Trip

   Coach Passengers/Flight Attendents             38.0
   First Class Passengers/Flight Attendents       11.0
   Passenger Trip Distance (sm)                  6621.     3682.     5754.     3452.
   Departures/Trip                              1.000     1.000     1.000     1.000
   Coach Load Factor                            0.650
   First Class Load Factor                      0.650

   Maintenance - System           ( 0.5000)      888.      602.      804.      579.
   Maintenance - Local            ( 5.2000)     3823.     3823.     3823.     3823.
   Aircraft Servicing - Aircraft Cont ( 215.00) 1288.      780.     1138.      741.
   Passenger Service - Cabin Crew  ( 63.55)     2926.     1772.     2585.     1682.
   Passenger Service - Food and Bev ( 2.0000)   2274.     1378.     2010.     1308.
   Traffic Servicing - Passenger Hand ( 11.00)  2088.     2088.     2088.     2088.
   Traffic Servicing - Bag and Cargo ( 80.00)   1028.     1028.     1028.     1028.
   Passenger Service - Comm/Publ/Res ( 0.0214) 26895.    14957.    23370.    14022.
   Cargo Service - Comm/Publ/Resrv ( 0.0120)      0.        0.        0.        0.
   General and Administrative      ( 0.0703)   10353.     6332.     9166.     6017.

   Total Indirect Operating Expense            51562.    32760.    46012.    31287.

   Total Indirect Operating Costs
      $/Trip-IOC                               51562.    32760.    46012.    31287.
      $/Flight hour                             8873.     9497.     8997.     9584.
      $/Block hour                              8606.     9026.     8691.     9083.
      $/Aircraft Mile                              7.79      8.90      8.00      9.06
      $/ASM                                    .026668   .030467   .027386   .031037

   IOC per Aircraft Trip Equation  = $  9202.12 + $  6.40/sm
   IOC per available seat trip     = $    31.51 + $0.0219/sm


 Total Operating Costs
    $/Trip-TOC                                157624.    96412.   139559.    91615.
    $/Flight Hour                              27125.    27950.    27290.    28063.
    $/Block hour                               26310.    26563.    26362.    26597.
    $/Aircraft mile                               23.81     26.18     24.26     26.54
    $/Available Seat Mile                      .081524   .089663   .083066   .090882

    TOC per Aircraft Trip Equation = $ 19717.89 + $ 20.83/sm
    TOC per available seat trip     = $    67.53 + $0.0713/sm
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    Breakeven Required Yield          ($/RPM)    .125422 .137944 .127793 .139819
       at Load Factors of .650 and .650




    Base ticket price for  6621.sm distance = $ 1854.01
    Based on Average Yield $/ASM of .140000 and .140000


  OliverIOC = .030467
  OliverTOC = .089663

============ AIRLINE RETURN ON INVESTMENT == 1992. DOLLARS ============

Trips/Year = 1102.     Trip Distance = 3682.(sm) = 3200.(nmi)

Average Yields:  First Class .130000   Coach Class .130000 $/RPM

Price (Mill. $)    ROI (%)      Total Operating    Direct Operating ($/ASM)
    340.313        5.600          .089663             .059197
    374.344        4.100          .093212             .062512
    408.375        2.700          .096761             .065828
    442.406        1.500          .100310             .069144
    476.438        0.400          .103859             .072459

Average Yields:  First Class .140000   Coach Class .140000 $/RPM

Price (Mill. $)    ROI (%)      Total Operating    Direct Operating ($/ASM)
    340.313        9.100          .089663             .059197
    374.344        7.300          .093212             .062512
    408.375        5.800          .096761             .065828
    442.406        4.500          .100310             .069144
    476.438        3.300          .103859             .072459

Average Yields:  First Class .150000   Coach Class .150000 $/RPM

Price (Mill. $)    ROI (%)      Total Operating    Direct Operating ($/ASM)
    340.313       12.100          .089663             .059197
    374.344       10.300          .093212             .062512
    408.375        8.700          .096761             .065828
    442.406        7.200          .100310             .069144
    476.438        6.000          .103859             .072459

Average Yields:  First Class .160000   Coach Class .160000 $/RPM

Price (Mill. $)    ROI (%)      Total Operating    Direct Operating ($/ASM)
    340.313       14.400          .089663             .059197
    374.344       12.800          .093212             .062512
    408.375       11.300          .096761             .065828
    442.406        9.800          .100310             .069144
    476.438        8.400          .103859             .072459


Manuf. Return on Investment  =  12. %
Airline Return on Investment =  12. %
Aircraft Price Mil $         = 340.313
Average Yield/RPM            = .149500
Production Quantity          =    504.




============ RETURN ON INVESTMENT, OPERATIONS == 1992. DOLLARS ============

Stage Length (nmi)     =    3200.        Utilization    =   1102.08 trips/yr
Initial Aircraft Price = 340.313         Tax Rate       =     34.00 %
Initial Investment     = 340.313         Interest Rate  =      8.00 %
Average Yield: Coach   = .140000         First Class    =   .140000 $/RPM

Year   (1-5)                    2001.    2002.    2003.    2004.    2005.
Annual Revenue                 107.838  107.838  107.838  107.838  107.838
Operating Cost                 115.833  115.238  114.595  113.901  113.152
  Interest                      27.225   26.630   25.988   25.294   24.544
  Depreciation                  15.314   15.314   15.314   15.314   15.314
Earnings Before Tax             -7.995   -7.400   -6.758   -6.064   -5.314
Income Tax                       0.000    0.000    0.000    0.000    0.000
Net Earnings                    -7.995   -7.400   -6.758   -6.064   -5.314
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Net Cash Flow                    -305.769   34.544   34.544   34.544   34.544
Discount Factor                     1.000    0.772    0.708    0.650    0.596
Discounted Cash Flow             -305.769   31.692   29.075   26.674   24.472


Year  (6-10)                        2006.    2007.    2008.    2009.    2010.
Annual Revenue                    107.838  107.838  107.838  107.838  107.838
Operating Cost                    112.343  111.468  110.524  109.505  108.404
   Interest                        23.735   22.861   21.917   20.897   19.796
   Depreciation                    15.314   15.314   15.314   15.314   15.314
Earnings Before Tax                -4.505   -3.631   -2.687   -1.667   -0.566
Income Tax                          0.000    0.000    0.000    0.000    0.000
Net Earnings                       -4.505   -3.631   -2.687   -1.667   -0.566
Net Cash Flow                      34.544   34.544   34.544   34.544   34.544
Discount Factor                     0.547    0.502    0.460    0.422    0.388
Discounted Cash Flow               22.451   20.597   18.897   17.336   15.905


Year (11-15)                        2011.    2012.    2013.    2014.    2015.
Annual Revenue                    107.838  107.838  107.838  107.838  107.838
Operating Cost                    107.214  105.930  104.543  103.045  101.427
   Interest                        18.607   17.322   15.935   14.437   12.819
   Depreciation                    15.314   15.314   15.314   15.314   15.314
Earnings Before Tax                 0.623    1.908    3.295    4.793    6.411
Income Tax                          0.212    0.649    1.120    1.630    2.180
Net Earnings                        0.411    1.259    2.175    3.163    4.231
Net Cash Flow                      34.332   33.895   33.424   32.914   32.364
Discount Factor                     0.356    0.326    0.299    0.275    0.252
Discounted Cash Flow               14.502   13.136   11.883   10.736    9.685


Year (16-20)                        2016.    2017.    2018.    2019.    2020.
Annual Revenue                    107.838  107.838  107.838  107.838  107.838
Operating Cost                     99.679   97.792   95.754   93.553   91.175
   Interest                        11.072    9.184    7.146    4.945    2.568
   Depreciation                    15.314   15.314   15.314   15.314   15.314
Earnings Before Tax                 8.158   10.046   12.084   14.285   16.662
Income Tax                          2.774    3.415    4.108    4.857   17.236
Net Earnings                        5.384    6.630    7.975    9.428   33.458
Net Cash Flow                      31.770   31.128   30.435   29.687   51.339
Discount Factor                     0.231    0.212    0.194    0.178    0.023
Discounted Cash Flow                8.722    7.840    7.033    6.293    9.985


Total
Annual Revenue                   2156.752
Operating Cost                   2125.076
   Interest                       352.920
   Depreciation                   306.282
Principle                         340.312
Earnings Before Tax                31.677
Income Tax                         38.180
Net Earnings                       27.528
Net Cash Flow                     346.416

Discounted Rate of Return on Investment   9.1 %


         **************************************************
         **                                            **
         **       End of ALCCA Economic Analysis       **
         **                                            **
         **************************************************
1
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APPENDIX F:            PROBABILISTIC LIFE CYCLE ANALYSIS OF COMBUSTOR

The NESSUS capability for the harmonic loads was used to compute the probabilistic responses of a combustor liner subject to high temperatures. Material properties were input using the elasticity matrix coefficients. Several NESSUS analyses runs were made for different degraded D-matrix coefficients due to the cyclic loads. Material degradation of these coefficients was performed using the multi-factor-interaction-model (MFIM). Probabilistic cyclic stresses and respective sensitivity factors were computed using NESSUS computer code. Hoop stress cumulative distribution function (CDF) for different load cycles at a critical node are plotted in Figure 1 and its sensitivity to the respective primitive random variables are shown in Figure 2. The temperature gradient at the location under study has been found most sensitive to the hoop stress.

Also, the material strength cumulative distribution function using the Weibull distribution was computed for different cyclic load cycles. The strength degradation was achieved using MFIM. Degradation due to both the temperature as well as cyclic load effects was accounted in the computation process. Figure 3 shows the CDF of strength under different load cycles. Using the results of probabilistic strength and stress, the life cycle curves at different probability levels generated as shown in Figure 4. Also, the probability of failure as well as survival probability curves for different load cycles were developed as shown in figures 5 and 6 respectively.
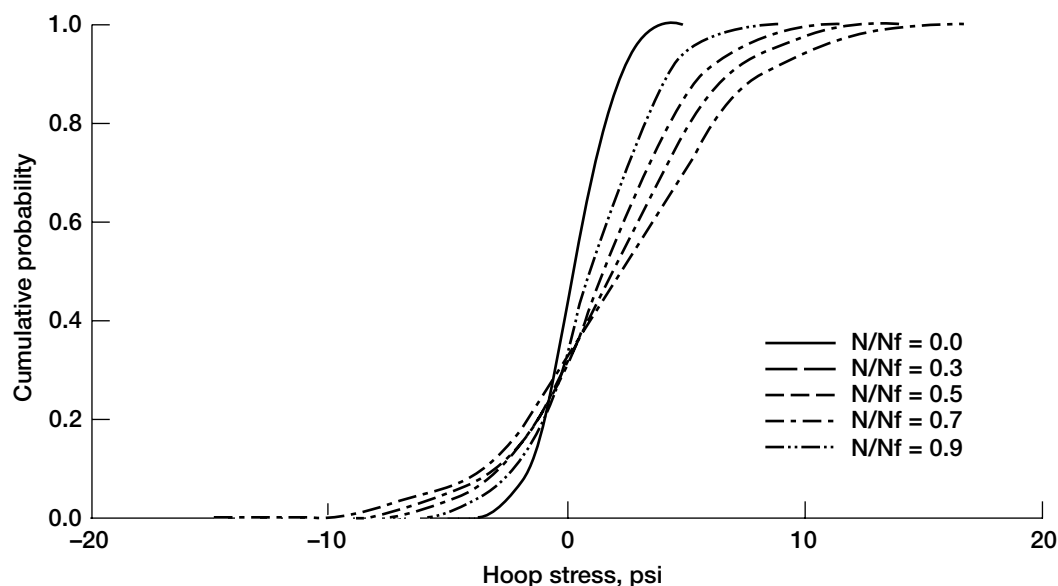


Figure 1.—CDF of hoop stress at a critical location for different load cycles.
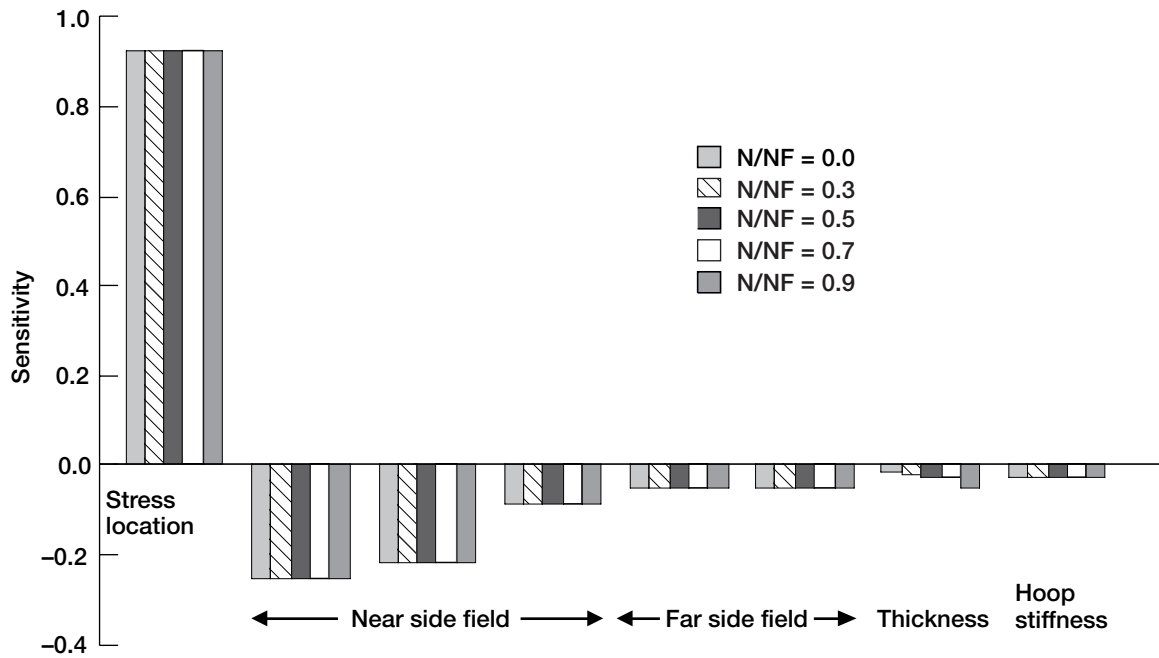
Figure 2.—Sensitivity of random variables to the hoop stress at different load cycles at 0.01 probability.
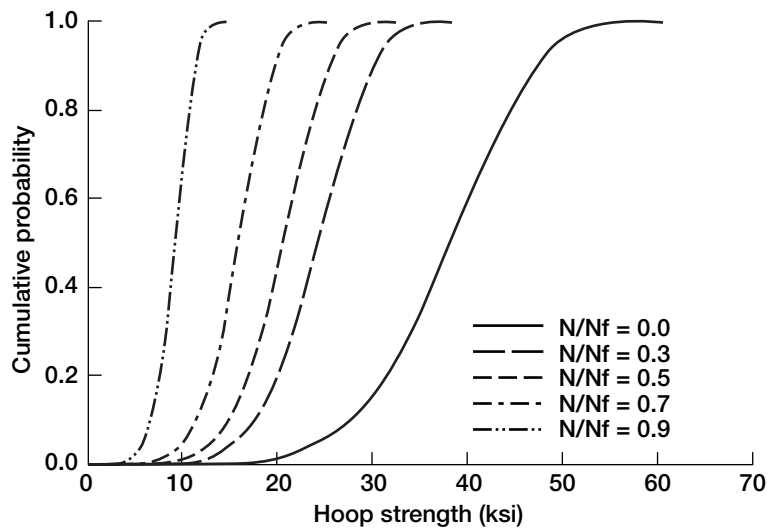


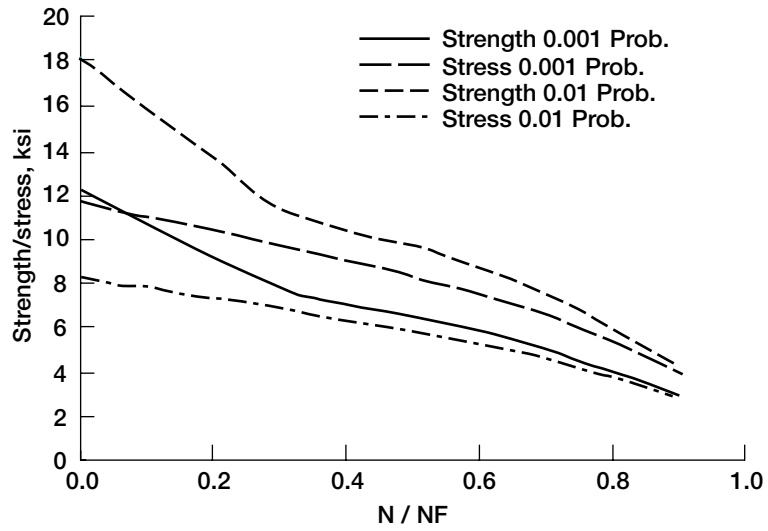Figure 3.—CDF of Hoop strength for different load cycles.

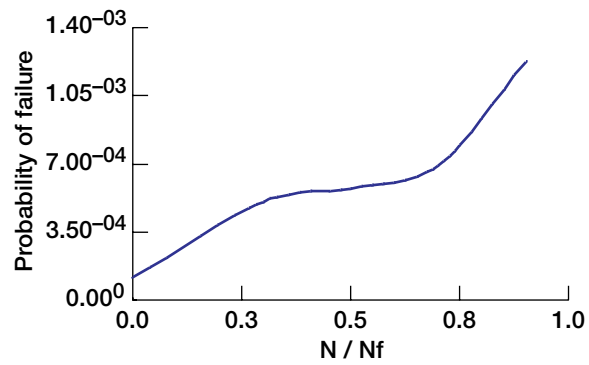Figure 4.—Strength vs stress at different load cycles.
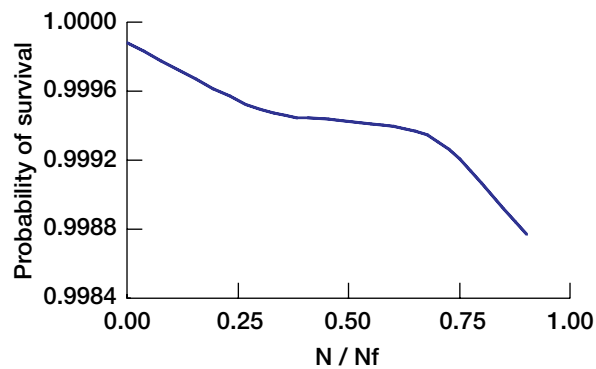


Figure 5.—Probability of failure.



Figure 6.—Survival probability.

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**13. ABSTRACT (*Maximum 200 words*)**

This report describes the work performed during the contract period and the capabilities included in the EST/BEST software system. The developed EST/BEST software system includes the integrated NESSUS, IPACS, COBSTRAN, and ALCCA computer codes required to perform the engine cycle mission and component structural analysis. Also, the interactive input generator for NESSUS, IPACS, and COBSTRAN computer codes have been developed and integrated with the EST/BEST software system. The input generator allows the user to create input from scratch as well as edit existing input files interactively. Since it has been integrated with the EST/BEST software system, it enables the user to modify EST/BEST generated files and perform the analysis to evaluate the benefits. Appendix A gives details of how to use the newly added features in the EST/BEST software system.

**14. SUBJECT TERMS**

Computer codes; Structural analysis; Aerodynamic analysis; Probabilistic evaluations; Damage tolerance; Systems evaluations

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